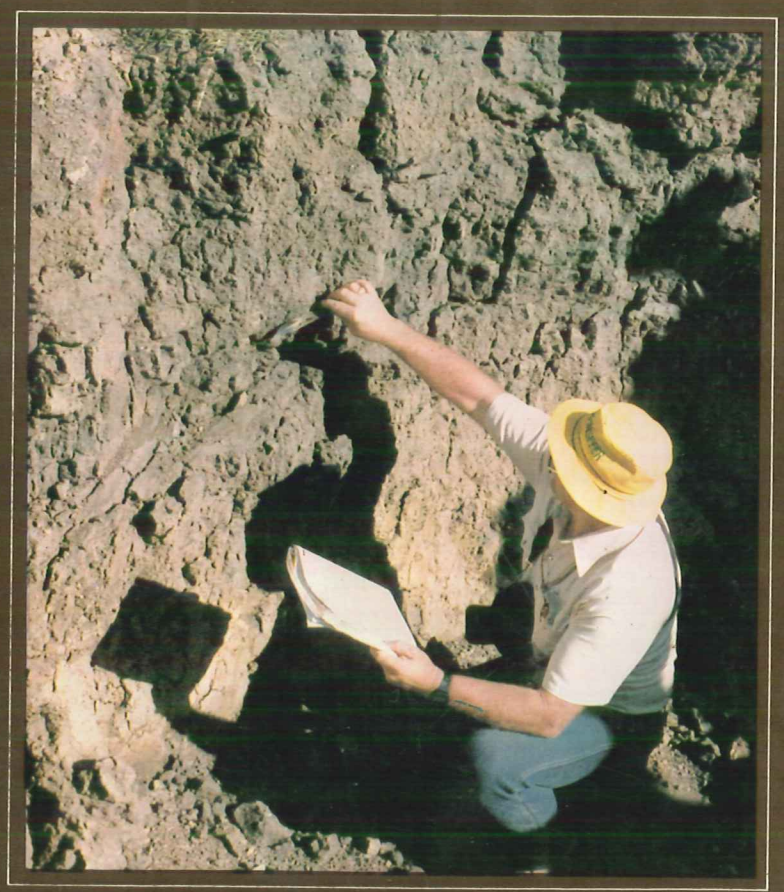
WETLAND SOILS: CHARACTERIZATION, CLASSIFICATION, AND UTILIZATION



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WETLAND SOILS: CHARACTERIZATION, CLASSIFICATION, AND UTILIZATION

Proceedings
of a workshop held 26 March to 5 April 1984
under the joint sponsorship of
The International Rice Research Institute

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Soil Management Support Services
Agency for International Development and
United States Department of Agriculture

* * *

Bureau of Soils
Philippine Ministry of Agriculture

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FOREWORD

The Workshop on Characterization, Classification and Utilization of Wetland Soils, held at the International Rice Research Institute (IRRI) 26 March-5 April 1984, produced recommendations for future research and actions to make the goal of greater crop production from wetland soils a reality. The workshop was jointly sponsored by the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) and the Soil Management Support Services (SMSS) of the U.S. Agency for International Development and U.S. Department of Agriculture.

The workshop brought together a unique mix of soil taxonomists and soil fertility scientists. Their meeting was combined with an interesting series of field visits in which participants were able to review rice production-experiments on many wetland soils. The workshop goal to unite these two groups to identify key problem areas for future research was fully realized.

Dr. Godofredo N. Alcasid, director, Bureau of Soils, Philippine Ministry of Agriculture and Food; Dr. Hari Eswaran, project coordinator, SMSS; and Dr. C. P. Mamaril, INSFFER coordinator, IRRI, coordinated the workshop. Dr. Martin A Raymundo, INSFFER consultant, organized the site visits.

Dr. Stephen J. Banta edited the proceedings with the assistance of Corazon V. Mendoza, assistant editor.

M. S. Swaminathan
Director General

WELCOME REMARKS

D. J. Greenland
Deputy Director General
IRRI

On behalf of the International Rice Research Institute I would like to extend to all of you a very warm welcome to IRRI, to our campus, which we share with the University of the Philippines, and to Los Baños. I would like also to extend a particular welcome to Dr. Alcasid, Director of the Philippine Bureau of Soils, and to Dr. Hari Eswaran, Project Coordinator of the Soil Management Support Services (SMSS), who have worked with us in the preparations for this meeting. It is a double meeting, that, as probably most of you realize, arose from a previous meeting of the International Network of Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) during a monitoring tour last year in Indonesia. INSFFER includes a regular annual visit of the collaborators in the network to one of the participating countries, both for a workshop to discuss activities and plan future activities and for a review in the field of some of the experiments being conducted. In the last 5 years or so, while we have been doing this, we have become increasingly aware of the need for and the importance of site characterization and the establishment of a method to relate soil fertility to other soils and other places where the results will be relevant. We had already made an approach to SMSS to see if they could assist some of the national programs, and the national soil surveys along with this. When Dr. Ivan Bunoan, Chief of the Soil Fertility Division of the Philippine Bureau of Soils, invited the INSFFER group to come to the Philippines this year, we thought it would be an opportunity to invite SMSS to come as well and to have a joint meeting and a joint discussion of the fertility of wetland soils and of their characterization and classification in relation to food production potential. I was very pleased indeed when Dr. Eswaran responded very positively to the suggestion. He has worked with us to put this meeting together and to get us assembled so that we can meet not only in the conference room but also in the field. We are very pleased to have been able to set up, with the help of the Philippine Bureau of Soils staff, what I hope will be an extremely interesting series of visits in the field where we can review both experiments and many wetland soils simul-

taneously. I am particularly delighted that there has also been such a positive response from those whom we have asked to come and join us in these discussions, to lead the presentations, and to contribute in other ways to the work of the meeting. Many of you have travelled far; some have travelled extensively from various parts of Africa and Latin America, as well as from North America and Europe. Those of us who are in our home base or from closer parts of Asia are pleased that you have taken the trouble to join us, and we look forward to having your inputs to our discussions.

I must add some words of thanks to our sponsors for the meeting. We are grateful to the SMSS, assisted by the U.S. Agency for International Development, which are represented here, for the support given us for the meeting. INSFFER receives support from the Swiss Government, whose help has enabled us to sponsor the participation of several of our collaborators and for which we are equally grateful. The Swiss Government has provided the wherewithal to maintain and conduct the INSFFER network successfully for several years.

While welcoming you on behalf of IRRI, I would also like to warn you at this stage that IRRI has the tradition, a well-established tradition now, of having a "show-and-tell" session in which you can all sit back and listen to people tell you what they have done. There is also during this meeting a field trip, when you can travel and enjoy some of the beautiful scenery of the Philippines. You will find that the field trip is also of very solid substance and that it will be quite hard work. A tremendous amount of effort has been put by several people into the preparations for the field trip. It will be a very enjoyable visit, but when you get back here after the trip, we intend to put you all to work. Then the "so-what" sessions will start. We are most anxious that from the "so-what" sessions we will produce several recipes for future research and future actions to make sure that from this workshop the plans for what we need to do, in relation to better characterization and classification of wetland soils for greater crop production, can become a reality.

The International Committee on Soils with Aquic Moisture Regimes of the SMSS is represented here by Prof. Moormann, who is Chairman. We are pleased that he has been able to join us, and I'm sure he will agree with me that there is much we still have to learn and to do to enable our classification work to help us grow, for Asia at least, more rice and for other parts of the world, maybe other crops, on the wetlands. IRRI's mandate is simply to help the world produce more rice. I hope this workshop is going to be constructive in advancing us further along that road.

Finally, I repeat, you are all very welcome; we are pleased that you have joined us for this meeting, and we look forward to a constructive 2 weeks, some hard work, and a very valuable report at the end that will illuminate the path ahead of us, in terms of both classification and characterization of wetland soils and for their better and more productive utilization.

G. N. Alcasid
Director
Bureau of Soils

On behalf of my agency, the Bureau of Soils of the Ministry of Agriculture, I welcome you all to the Philippines, which I am sure you will find a very good laboratory for looking into the problems of wetland soils. Right now, the Philippines is undergoing a lot of changes because of the economic situation, and in a developing country like ours, whenever the economy is in crisis, the country's natural resources are overburdened -- forests are overcut, minerals are overdug, and agriculture is overstretched. The Philippines is basically an agricultural country, and the agricultural sector has again been tasked with providing the bulk of the solution to our current problems.

Today we are gathered together to look into the problems of classification of wetland soils, both naturally wet and artificially wet. Many have studied their respective potentials in specific areas and their limitations as well, although some countries have done this superficially and some in more detail. Our experience in the Philippines, as a developing country, is worthwhile to share, and we would like also to learn from developed and other developing countries. Rice is our staple food, and, as the saying goes here in the country, "Where rice grows, so does the economy." Probably that was very true in the past, but now the rice situation in the country is quite good; through new technology and increased irrigation, we have turned the Philippines from a rice importer to a rice exporter in a few short years. Although rice may be under control at present, our economy still has to be helped. Imports, specifically of food such as wheat, soybean, and milk, must be reduced. In the reduction of food imports the wetland soils, our present rice lands, are being eyed. Traditionally only about one-third of the lands irrigated during the rainy season are irrigated during the dry season, and we have about 3 million ha under irrigation, so about 2 million ha are not being planted to rice during the dry season. These 2 million ha are thus available for additional food production. But the questions are, "Where are they; what are their characteristics; what are they good for?" Decisions must be made, and directions must be set today. In fact, just recently we had a 2-week forum on Soil taxonomy again supported by SMSS. Most of the participants were Bureau of Soils employees and soil taxonomists or soil classificationists from the different agencies of the government, including the academic institutions. Thus we are building up, because we need to have more concrete decisions and more concrete

directions. I am confident that this forum can open up most of the least-understood areas. We shall therefore be here with you, listening and participating intently because we, too, need to find a better direction. I know that the field trip will be a very good laboratory for this particular exercise, and I wish you a very pleasant stay in the Philippines.

Thank you.

H. Eswaran
Project Coordinator
SMSS

All of us are aware that in the next 20 years the world will have to feed an additional 2 billion or so people. We are also aware of the dramatic contributions of national institutions and international centers like IRRI to research and development. Yet these contributions become meaningful and our goals to sustain production feasible only if the technology is transferred to the farmer. Unfortunately, the development of operational mechanisms for the efficient diffusion of agroproduction technology work horizontally and vertically has lagged behind the technology-generation process, with which most of us here are involved. This is a subject of research and discussion that we may only touch upon during this workshop.

The major objective of this workshop, however, is, at least in our view, to provide the prerequisites for the effective transfer of the agrotechnology that we generate. One of the constraints to the transfer mechanism has been the lack of a common language among soil scientists. We now have Soil taxonomy, which has emerged as a de facto international classification system. The Soil Management Support Services (SMSS), which I represent, a project of international technical assistance on soils survey and classification of the United States Agency for International Development and implemented by the Soil Conservation Service of the U.S. Department of Agriculture, is committed not only to assist countries in using this system, but to refine it so that it is better applicable to the soils of the intertropical areas. This workshop is the 7th International Workshop organized by the SMSS, and we are indeed glad that we could organize it in collaboration with IRRI and the Bureau of Soils of the Republic of the Philippines. We have 2 groups of people with us here -- one group interested mainly in morphology, genesis, and classification, and the other in the use and management of the soils -- and our goal in the next 2 weeks is to unite these 2 groups. We have made every attempt to bring together the leading scientists in these areas, particularly those interested in wetland soils. I would like to focus on what SMSS expects from this meeting. During the development of Soil taxonomy from 1950 to 1975, because of a lack of data, the classification of soils of intertropical areas, specifically the rice-growing soils, was not as satisfactory as that of their temperate counterparts. In Asia, the farmer himself creates the environment for growing rice. He induces an aquic moisture regime on an otherwise well-drained soil. Through generations of this

practice he sometimes develops a pan in the subsoils of these soils. We do not have proper position studies of these anthropogenic soils; this, by itself, is a sufficient reason for having a workshop. Can we classify these soils in Soil taxonomy?

The answer is "yes," or, more specifically, we can give these soils a name. However, that is not the purpose of Soil taxonomy. We must be able to interpret from the name, and this is perhaps where Soil taxonomy uniquely differs from other classification systems. I believe that with some refinement we can make Soil taxonomy better applicable to these soils so that it truly becomes a vehicle for agrotechnology transfer. Because of the concern of several soil scientists in this area, we have formed the International Committee on Soils with Aquic Moisture Regimes (ICOMAQ), under the chairmanship of Dr. Frank Moormann. The charge of ICOMAQ is to propose changes in Soil taxonomy to handle rice-growing soils. We will spend considerable time during this workshop discussing the responsibilities of ICOMAQ.

I would like to emphasize one thing from the SMSS point of view. This is not a conference organized by some scientific society, where the task of the participant ends after his paper presentation. We expect the involvement of all the participants, and discussion is a key activity. We expect that key problem areas will have been clearly identified by the end of the workshop. Accordingly, we have identified leading scientists who will make summaries of these areas. We expect some resolutions on some of the more obvious classification problems. We also hope that by the end of the workshop all key research areas will have been identified so that coordinated research may be undertaken. We are also confident that this workshop will create an awareness for the judicious use of wetland soils and that a group of people present here, together with others will continue to work for the better understanding and utilization of these soils. Finally, I wish to say that the organizing committee has developed a tight program for the next 2 weeks. The staffs of IRRI, the Bureau of Soils, and SMSS have spent much time and effort in planning this International Workshop on Characterization, Classification, and Utilization of Wetland Soils, and it promises to be an exciting one.

Thank you.

OPENING SESSION

CHARACTERIZING AND CLASSIFYING WETLAND SOILS IN RELATION TO FOOD PRODUCTION

R. L. GUTHRIE

Wetland soils are extensive throughout the world except in major deserts. In temperate zones, large areas of wetlands suitable for food production have already been developed. In South America and Africa, large areas with potential for food production remain undeveloped; the tropical climate and increasing demand for food, including rice, make wetland soils on these continents especially attractive for agricultural development. Wetland soils have distinct advantages and disadvantages for food production. In addition to their ample water supply, they are usually level and often occur in large land units, making large-scale farming feasible. Other advantages include low erosion hazard and moderate to high inherent fertility. Major disadvantages include cost of development and difficulty of management. Some wetland soils have special problems such as salinity, high Na content, low pH, or poor physical properties following drainage.

Wetlands are essential breeding, rearing, and feeding grounds for many species of fish and wildlife. They are also important for producing food for humans and domestic animals. International recognition of these sometimes conflicting values has led to an ever increasing need to classify and characterize wetland soils in relation to food production.

Some of the issues that must be dealt with include the potential of wetland soils to produce food, development costs, and conflicts between agricultural development and other land uses. Before making decisions about the use of wetland soils or projecting estimates of their food production potential, it is necessary to identify these soils and determine their extent and distribution.

Wetlands in the United States are defined as those lands where saturation with water is the dominant factor determining the nature of soil development and

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the types of plant and animal communities. This definition focuses on soil as an integral component of wetland systems and allows soil classification and soil surveys to be used as tools for identification. The concept of saturation with water as a dominant factor in determining the nature of soil development is the basis for the definition of the aquic moisture regime used in Soil taxonomy (16), the United States Department of Agriculture soil classification system. Soil taxonomy is used widely throughout the world and has proven to be a useful tool for inventorying soil resources (3).

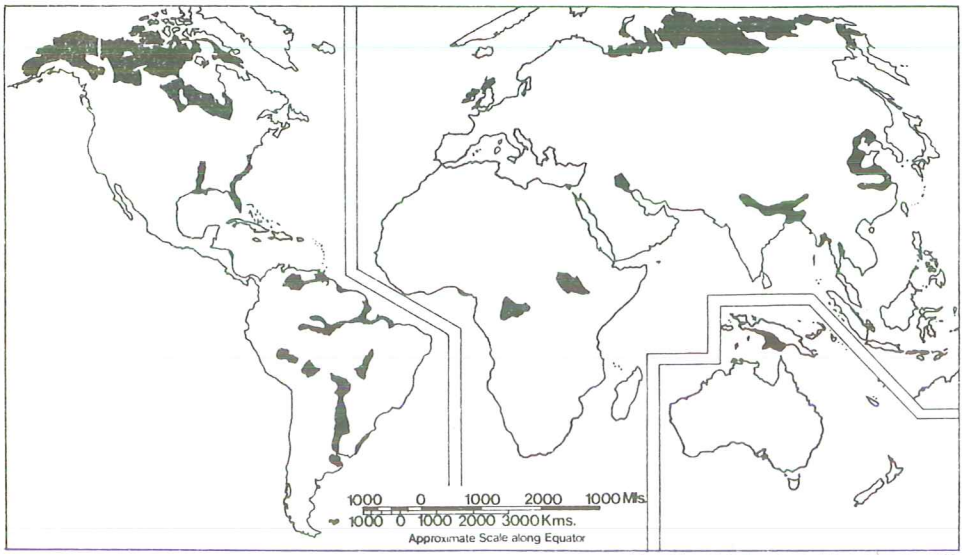
A discussion of food production on wetland soils must center on rice, although many other crops can be grown quite productively on these soils with adequate water management. Rice is grown throughout the world and is the world's most important single food crop (2). It is the primary food in Asia and is rapidly gaining acceptance in Latin America and Africa, where the potential for increased production from expanding the area of cultivable land is enormous.

Research in traditional rice-growing areas has concentrated on plant breeding and crop protection, because land decisions were made long ago. Substantial increases in production have resulted, but as rice became an important food throughout the world, the emphasis shifted to expansion of production into new areas. Soil scientists began to play a strong role, both in making soil resource inventories and in production research.

In the major rice-producing area of the United States, land drainage has made it possible to grow a variety of other crops such as soybean and cotton in rotation with rice (8). Throughout the Caribbean area, sugarcane is grown on wetland soils. In Guyana and Surinam, sugarcane is produced on wetlands that were reclaimed from the sea. In many tropical areas with wet and dry seasons, a second crop can be grown after rice before the moisture supply is exhausted.

DISTRIBUTION AND CLASSIFICATION

The wetland soils of the world make up about 10% of the world's land mass (Fig. 1). The principal suborders of wetland soils and their distribution are given in Table 1. Moorman (9) reviewed the classification of rice soils in a recent paper, including the classification of most wetland soils of the tropics. Because climate is a major factor in agricultural production, the following discussion is divided into two parts: nontropical and tropical.



Adapted from U. S. Department of Agriculture, May 1972

1. Areas dominated by wetland soils.

Table 1. Distribution of principal wetland soils of the world (16).

Soil	Area (ha x 10^6)	Fraction of world land mass (%)
Aquent	77.7	0.6
Histosol	129.5	0.9
Aquept	984.2	7.5
Alboll	51.8	0.3
Aquod	7.8	0.1
Aquult	51.8	0.4

Nontropical wetland soils

Nontropical wetland soils

Large areas of Aquepts and Histosols dominate landscapes in Alaska, Canada, and Russia, but these soils have little or no potential for food production. Short growing seasons followed by long periods when the ground is frozen make it impractical to drain these soils and impossible to grow crops other than vegetables on them.

Wetland soils occupy large areas in the middle latitudes of the northern hemisphere. One of the largest areas is in the delta of the Mississippi River in the United States. Most of the land in this area has been drained and is now producing crops.

Haplaquepts, Ochraqualfs, and Udifluvants (1) are the dominant soils; they are fertile, generally flat, and variable in texture. Histosols and Hydraquents are extensive in the southern part, where a large percentage of the land remains in forest. Major cultivated crops are rice, cotton, and soybean.

The Atlantic and Gulf Coastal Plains area is the largest area of wetland soils in the United States and is the area with the most potential cropland (1). As most slopes are gentle and most soils are loamy, drainage and farming with large mechanized equipment are feasible. Inherent fertility is low and soil acidity is a problem, but most soils are responsive to fertilizer and lime. Haplaquods, Ochraquults, Paleaquults, and Paleudults are the most extensive soils. Rice and cotton were once significant, but now the most important crops are soybean, maize, peanut, and forage crops. More than half of the 14 million ha of potential additional farmland in the southern United States is in this area.

One other large area of wetland soils in the northern middle latitudes is northeastern China, where Aquents and Aquepts are extensive. Most soils have been drained or otherwise altered so that water can be controlled. Rice is the major crop, although many other food crops are grown on soils that are not too wet.

The principal area of wetland soils in the southern hemisphere outside of the tropics is in Argentina, where a relatively large, nearly level area dominated by Albolls occurs in the northeastern portion of the country. Slopes are gentle and the soils fertile, although many of them are clayey. Drainage is often difficult, but many of the soils dry out enough during the growing season to allow cropping. Crops are mixed, although soybean now dominates in some areas.

Tropical wetland soils

Wetland soils are fairly extensive throughout the humid tropics. South and Southeast Asia have the highest percentage, although large areas exist in South America. Africa has a few large areas, but they constitute only a small percentage of the land mass. Osborn (11) pointed out that Africa, which represents one-fifth of the world's land, is about one-third desert, and that all of its irrigated land makes up only 0.1% of the continent. Wetland soils occupy a larger area than irrigated land, but compared to the total the area is still quite small. There are, however, several large areas, principally in central Africa, where wetland soils are common. Both areas are dominated by Tropaquepts and Tropaquents, although

soils with better natural drainage are intermingled. These soils vary in texture and chemical properties and have limited suitability for conversion to productive use.

Tropical South America probably has more wetland with high potential for development than any other continent. A high percentage of its wetland soils lie in the Amazon basin, which occupies approximately 40% of the continent (11). Tropaquepts and Plinthaquults are associated with Oxisols and other Ultisols on the floodplain and terraces of the Amazon. Most of the soils in this area are undeveloped and remain covered with rain forest.

In northern South America, coastal areas in Venezuela, Guyana, and Surinam are dominated by wetland soils. In Guyana and Surinam, most wetland soils are planted to sugarcane and other food crops, including rice. The dominant soils are Tropaquepts and Tropaquents. In Venezuela, many of the wetland soils are used for pasture as well as for sugarcane and rice. In this area, large expanses of Vertisols are associated with Tropaquepts and Plinthaquults. The Rupununi savanna in Brazil and Guyana is a region typified by a long wet season and dry season. As a result, most soils are either flooded or waterlogged, or both, for many months. Plinthaquults and Paleaquults are extensive and intermingled with Paleudults. This region, which occupies more than 2,700 km^2 in Guyana alone (7), is largely undeveloped except for livestock enterprises.

The proportion of wetland soils to total land area is probably higher in South and Southeast Asia than in any other major tropical region of the world. In India, West Bengal has a large concentration of Ochraqualfs, Haplaquepts, and Haplaquents (10) ranging in texture from sandy loam to clay and formed mostly in old alluvium. Most of these soils, which are already producing rice, are very productive.

Wetland soils in Sri Lanka are located mainly in inland valleys, although some are on coastal plains (12). Many of the inland valleys, where most of the wetland soils produce rice, are dominated by Aqualfs and Aquults. Aquepts and Hemists are locally extensive on minor floodplains and on coastal plains. Most of these soils have low pH, low CEC, and low base saturation.

The major wetland soils in Malaysia are Aquepts and Aquents (13). Most were formed in marine or alluvial sediments and are the least productive rice soils in the country. Low pH and, in some areas, sulfates retard rice production.

Aquepts dominate the wetland soils of Indonesia (15), some of the largest areas being on the north coast of Java and on the east coast of Sumatra.

Natural fertility is moderate and physical properties are relatively good, making these soils moderately good for rice, which is the main crop. Sulfur deficiency may be a problem in some of these rice soils.

Other countries where wetland soils are important are the Philippines, Kampuchea, Laos, Vietnam, and Thailand (6). Aquepts and Aquents dominate wetland areas and occur mainly on alluvium and coastal plains. Aquents and Aquepts are especially important in the Mekong River Delta in southern Vietnam and in the Red River Delta in northern Thailand. Deepwater rice production is important on some of these soils in Thailand. Histosols are locally important in Southern Vietnam and in the Philippines. Rice is the major crop in all of these areas.

POTENTIALS AND LIMITATIONS

Characterizing wetland soils in relation to food production must take into account their advantages and disadvantages. Regardless of their geographic location, these soils share many common properties. Properties of some wetland soils are listed in Table 2. Other factors that influence the potential productivity of wetland soils are their level topography, minimal soil erosion, natural fertility, and location in climatic regions of adequate rainfall for most crops.

Level topography

Most wetland soils are on level to gently sloping terrain and have poor natural drainage. Many areas are on coastal plains, deltas, and broad floodplains. When drained, these large tracts allow efficient mechanized farming operations.

Minimal soil erosion

Gentle slopes and the possibility of water table control in wetland soils make it possible to maintain low levels of soil loss due to erosion. Wetlands offer a unique opportunity to expand the land base for food production without increasing the risk of soil degradation. However, many of these soils have not been previously placed in production because of physical and chemical limitations, which must be overcome before they are made productive.

Fertility

Fertility levels have a direct bearing on the potential for development of wetland soils, especially in developing countries where fertilizer and lime are

Table 2. Diagnostic and associated properties of some wetland soils.

Classification	Morphological	Physical/chemical
Tropaqualf	Long periods of wetness each year	High base saturation
Tropaquents	Long periods of wetness each year	Variable texture, moderate fertility
Fluvaquents	Annual flooding, variable wetness	High fertility, stratified textures, moderate organic matter
Hydraquents	Permanent wetness	Low strength, irreversible hardening upon drying
Sulfaquents	Long periods of wetness each year, tidal influence	Extremely low pH after drainage
Tropaquepts	Long periods of wetness each year	Moderate fertility, variable textures
Halaquepts	Long periods of wetness, tidal influence	High sodium, salt spray
Argialbolls	Seasonal wetness, eluvial/illuvial horizon sequence	High fertility, high organic matter
Ochraquox	Seasonal wetness, minimal profile differentiation	Low CEC, low fertility
Tropaquods	Long periods of wetness each year, podzolic profile	Variable charge clays, sandy, low fertility
Plinthaquults	Long periods of wetness each year, plinthite, eluvial/ illuvial profile sequence	Low fertility, low pH
Tropaquults	Seasonal wetness, eluvial/illuvial horizon sequence	Low fertility, low pH

often scarce. Guyana, for example, has no source of limestone and no fertilizer plants within the country. Fortunately, the coastal wetland soils in that country require no lime and little fertilizer except N. Wetland soils of the Rupununi savannas, however, are acid and low in fertility. Crop production in that area would require fertilizer and lime.

Many of the wetland soils that have potential for agricultural development are forming in young alluvium or coastal marine sediments. As a result, most are nonacid and have at least a moderate level of fertility. After drainage, these soils can be farmed successfully with a minimum of inputs.

Rainfall

With notable exceptions such as the Nile Delta, most wetland soils are in climatic regions typified by abundant rainfall. The climatic factor that makes the soils wet becomes an asset after they are drained. Water management makes supplemental irrigation possible and also provides water for flooding rice fields. Dryland crops can be grown successfully during the dry season without the expensive irrigation that would be necessary in drier areas.

PROSPECTS FOR FOOD PRODUCTION

Wetland soils have many advantages for food production, but they also have disadvantages. One of the major disadvantages is the cost of development and maintenance. Often forests must be cleared before drainage work, which requires large expenditures for construction and maintenance, can begin. Intensive water management is usually required and often calls for sophisticated construction work as well as well-trained management personnel.

Wetland soils in some areas have special problems. Acid sulfates are common in many estuarine areas. Upon drainage, these soils become so low in pH that crops cannot be produced. Other wetland soils dry irreversibly after drainage and are unsuitable for cultivation. Certain soils, especially those in coastal areas, are saline, and only salt-tolerant crops can be grown. As many soils formed in sediments are clayey and poorly aggregated, tillage is often a problem, and successful seeding, cultivation, and weed control require careful management.

Nevertheless, as populations increase in developing countries and the pressure for increased food production grows, efforts must be made to expand the area of arable soils. According to Crosson and Frederick (5), the total of current and potential agricultural land in developing countries is 1.6 million ha, but only 32% of that land is now used. Much of this land is in upland areas, but a significant portion of it is in wetlands such as those in the United States, where 14 million ha of wetland soils are available compared to 118 million ha now planted to crops (1). With drainage and proper water management, these soils offer gentle slopes, good fertility, low erosion, and abundant rainfall. Conditions for growing rice as well as many other food crops are better on these soils than on most upland soils as long as water can be controlled and utilized. Indeed, the greatest potential for expansion of food-producing lands may be in wetland soils.

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PURPOSE OF THE WORKSHOP

CONSTRAINTS TO RICE PRODUCTION AND WETLAND SOIL CHARACTERISTICS

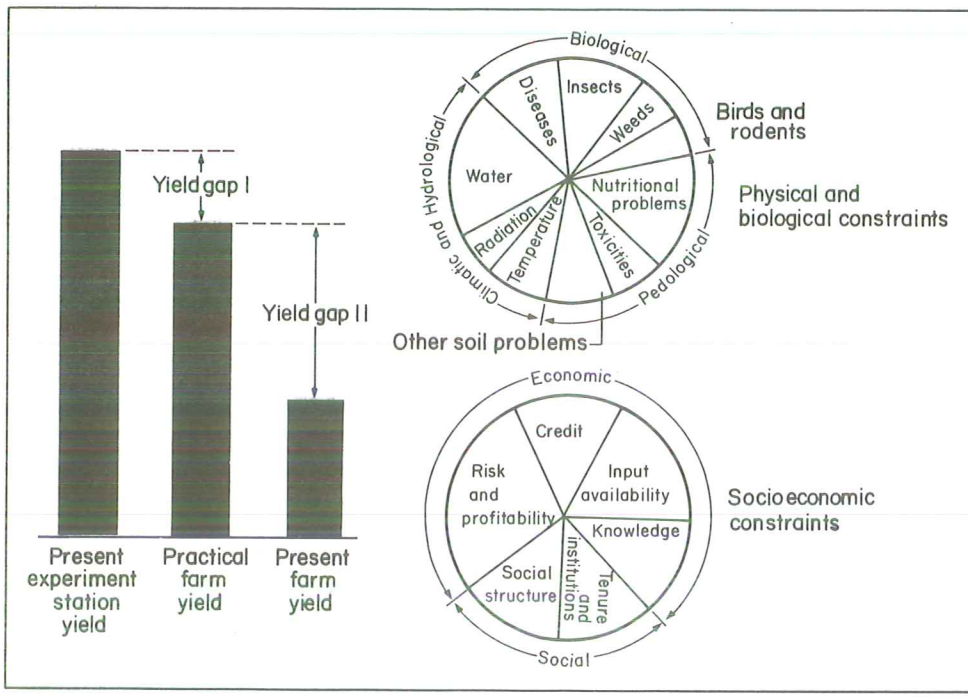
D. J. GREENLAND and S. K. DE DATTA

Constraints to rice production in wetland soils arise from climatic, hydrological, and economic factors, as well as from soil factors. Where water cannot be fully controlled to provide continuous, shallow flooding of the soil, water shortage and crop submergence are common problems. Stagnant water conditions are often associated with low redox potentials and hence with toxicities of Fe and sometimes of other elements. Nutrient deficiencies are common in wetland soils, although P is more available in waterlogged than in drier conditions, and K is often in good supply in wetland soils. Structural conditions appropriate for rice production are those that maintain water in the soil and are totally different from the aggregated condition normally considered desirable. What is desirable in wetland soils is the ability to reaggregate after being used for rice, to allow an upland crop to be grown subsequently. Classification systems, to be useful for extrapolating management information, must take into account these constraints.

Constraints to rice production arise from many factors. Aside from soil constraints there are important hydrological and climatic factors as well as biological factors that determine the water regime. For the individual farmer, several social and economic constraints also exist and are frequently important determinants of actual production (Fig. 1; 22). Hydrological and climatic factors determine the type of rice production system practiced.

In this paper, we describe the major physical constraints to rice production and relate them to wetland soil characteristics in the hope of assisting the development of a classification system for wetland soils that relates their characteristics to their

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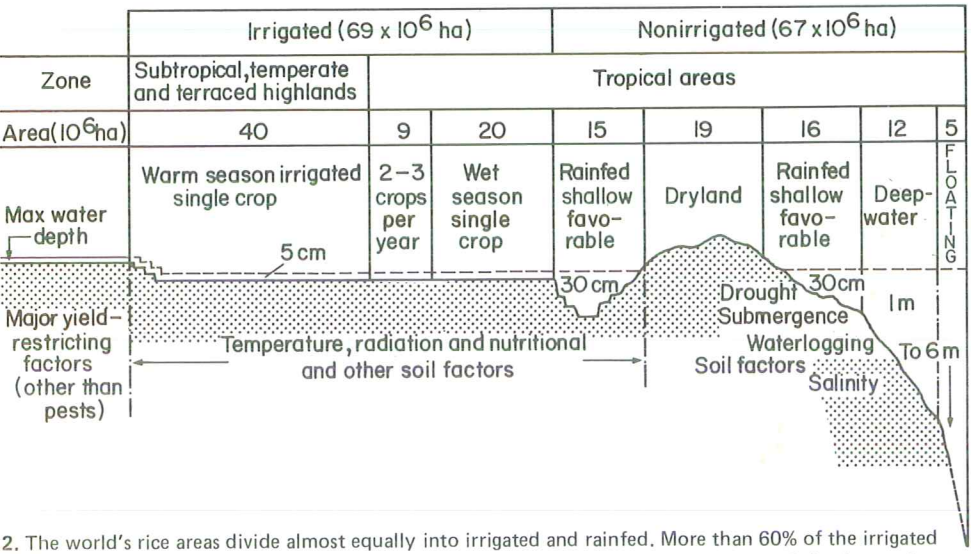


1. Factors contributing to the gap between present and practical farm yields. Some physical and biological constraints also contribute to the gap between practical farm yields and experiment station yields.

production capabilities. IRRI (24) has recently reviewed the existing systems of classification of rice production environments (16). That adopted by Khush (28) endeavors to embrace in a simple form the components of different systems that relate to the breeding of rice varieties and the development of management methods suited to each.

The wetlands where rice is grown include the great estuarine areas of Asia as well as many smaller river valleys and floodplains. Most of them occur in the monsoonal areas and are subject to alternate periods of flood and drought. Where water is not fully controlled by appropriate engineering works, rice will usually be subjected to submergence or drought, or both. These wetlands also include substantial areas with specific adverse soil conditions such as tidal salinity, acid sulfate, and peat formation (Fig. 2; 21).

Much specific information on the soils of these areas has been assembled in Soils and rice (20), Soil-related constraints to food production in the tropics (25), Rice: soil, water, land (33), and the Proceedings of the symposium on paddy soils (1). From these publications, it is well established that under existing classification systems a wide range of soils are included in the wetland areas. In this paper no attempt



2. The world's rice areas divide almost equally into irrigated and rainfed. More than 60% of the irrigated area is, however, in China and India. Only about 20% of the rainfed area — shallow rainfed — has environments favorable for rice growing.

is made to relate constraints to the groups of the existing classification systems. Instead, specific soil characteristics associated with different constraints to crop production are discussed.

CONSTRAINTS ASSOCIATED WITH WATER DEFICIENCY

A deficiency of water stands out as the most serious soil-related constraint to rice production in Southeast Asia (3). Several factors contribute to this little recognized fact. First is the erratic nature of rainfall in much of Asia (50). Rice is an exceptionally shallow-rooted crop (36, 49), and until recently little had been done to improve its rooting habit. Also, the practice of soil puddling to reduce percolation and to destroy weeds limits the ease with which rice roots can explore a greater soil volume. Water deficiency is most important in those areas IRRI (28) denotes as "rainfed, shallow, and drought-prone," of which there are about 5 million ha in northern and northeastern India and smaller areas elsewhere. It also occurs in the areas described as "rainfed, shallow, drought and submergence prone," of which there are about 3 million ha in northeastern Thailand and 0.5 million ha in Laos and Kampuchea. Drought may also be a problem from time to time in irrigated and "rainfed, shallow, favorable" environments, as the source of water is often a perennial stream diverted to supplement the natural rainfall and does not give an assured water supply. Furthermore, the "deepwater" and "very deepwater" or

floating rice areas are often subject to drought at the early stage of crop development, before monsoon floods arrive. Thus, those soil characteristics related to water storage, accessibility to water stored in the subsoil, and presence and accessibility of a water table should be given due attention in characterizing and classifying wetland soils.

Certain special considerations arise because of the process of puddling wetland soils (7), which may considerably reduce the volume of the pores that store the water available to roots (storage pores, approximately 0.5–50 μm in diameter) and induce formation of a pan that restricts root penetration (19). Quantitative information on the formation, strength, and persistence of such pans is needed and should be used to characterize wetland soils.

The presence of a water table within the soil where it can influence water available to the crop is also obviously important. A fluctuating water table within the soil profile induces easily recognizable characteristics in the soil. These hydromorphic features have been widely used in different systems for the classification of wetland soils (32). Emphasis is usually given to their morphological effects; it should perhaps be directed more specifically to the influence the water table may have on crop production and its influence on the redox potential within the rooting zone.

CONSTRAINTS ASSOCIATED WITH EXCESS WATER, INCLUDING WATER STAGNATION PROBLEMS

Flooding with consequent crop submergence is a problem in many of the lower lying wetlands of Asia. Frequently associated with crop problems is excessive soil reduction, recognized by the terms "stagnant water" or "waterlogged" that are frequently used to describe much of the rice production areas of eastern India (9) and Bangladesh. IRRI describes these lowland areas, which are usually flooded to depths of about 50 cm, as "rainfed, medium-deep, waterlogged." Their limitations to crop production appear associated primarily with extensively low reduction potentials and, perhaps partly because of this, low P availability. In the "deepwater" (flooding to depths of 50 cm to 1 m) and "very deepwater" (>1 m) areas, the principal problem of rice production is the tendency for the rice crop to be submerged for periods of up to 10 d, and the need is for rice varieties able to tolerate such prolonged submergence and in addition able to elongate rapidly and over a long period as the floodwaters rise. Submergence tolerance and elongation ability are properties that De Datta and Abilay (10) and De Datta

(9) include as important requirements for adaptability of rainfed lowland rice to flood conditions. In these areas, severe reducing conditions in the soil associated with inadequate surface drainage are also a constraint to crop production.

There are at least 6-7 million ha of medium-deep waterlogged rice lands in eastern India, Bangladesh, and other parts of South and Southeast Asia. Rice yields in these areas are very low and have languished at levels close to or below 1 t/ha for many years. The soil characteristics that determine the low productivity of these soils must still be defined adequately. Ponnamperuma (39) states that soil submergence may lead to excessive reduction of Fe, but because of the high level of Fe^{2+}, S^{2-} will be precipitated as it is formed and so is unlikely to be a serious toxic factor. Similarly, although soluble Mn may reach a very high level, rice plants are generally able to tolerate it. Transient S^{2-} may possibly be sufficiently toxic to reduce yields, since Shu-zheng et al (44) have shown, using a S^{2-}-selective electrode, that precipitation by Fe^{2+} is far from instantaneous.

The oxidation-reduction potential changes in waterlogged soils and the contributions of assimilable organic materials to these changes are now well understood (37, 38, 40). However, we badly need a simple method of quantifying the dynamics of the oxidation-reduction system that can be used to characterize soils in relation to rice production.

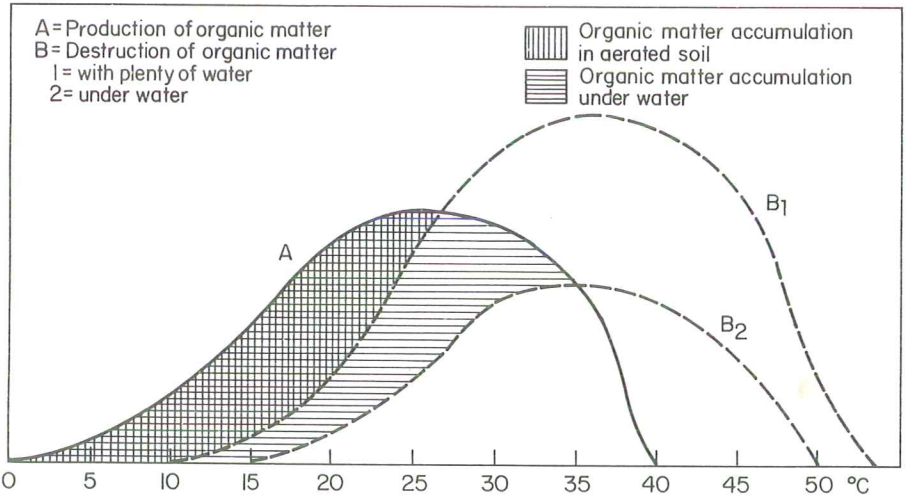
For most soils subject to excess-water conditions, drainage is not a practicable solution as it requires major engineering works covering very large areas and is therefore extremely costly. However, problems of excessive reduction are not confined to flooded areas. The lower lying lands in many irrigation systems may become waterlogged if, as frequently occurs, inadequate attention is given to surface drainage. Adequate water movement through lowland rice fields is recognized by most rice farmers as essential. Incoming water is normally well aerated, and the O_2 in the water prevents the redox potential from falling too far and helps to maintain the buffering effect of ferric and manganic oxides. For good root development throughout the soil profile, it is important that some vertical percolation be maintained. A Chinese "rule of thumb" is that 10 mm/day is needed for rice yields exceeding 6 t/ha. This is most probably associated with ensuring good root development and maintenance of root activity. Because the redox potential is dependent on assimilable organic matter levels in the soil, it may also be related to the use of large amounts of organic manures. The relevance of these findings must be evaluated in the lowland tropics. The higher temperatures will produce a more rapid turnover of organic material, and hence a

more fleeting existence of inorganic or organic toxins. Again, simple characterization of the redox system is needed.

CONSTRAINTS ASSOCIATED WITH NUTRIENT DEFICIENCIES

Much attention has been given to the constraints to rice yields caused by nutrient deficiencies and their correction through proper fertilizer management (7, 11, 26). Nitrogen deficiency is extremely common. Even in "waterlogged" soil areas, soil N levels tend to be low. Mohr and van Baren (32) published a temperature/organic matter curve for paddy soils (Fig. 3) based on field experience. This indicates that, in the reduced condition, mineralization of organic N will proceed as rapidly as in aerated conditions provided the mean annual soil temperature exceeds 32°C. This finding has recently been confirmed for the paddy soil at IRRI by Neue (34) using ^{14}C-labeled rice straw. However the relation between soil N, mean redox potential, temperature, and mineralization needs much further study before the relation between soil organic matter level and N supply can be fully understood. Total N may be an adequate guide to N release provided that other factors affecting the rate can be identified. Neue (34) has identified several of these factors. The dynamics of soil N has recently been summarized by Mengel et al (30). Factors related to the amount and mineralization of organic matter in wetland soils should be determined and used in their characterization and classification.

The inorganic forms of P are usually present at higher levels in flooded soils than in upland soils.



3. Range of destruction and accumulation of organic matter as related to temperature (32).

Thus P is less commonly deficient for rice than for upland crops. Nevertheless, it is still a frequent constraint to rice production. For example, in experiments in five countries under the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) program, the grain response to P was as much as 1.3 t/ha provided P was applied together with N (8).

Experiments by Roy and De Datta (41) showed that reduction of the soil by flooding decreases P sorption by 28-70%. In a subsequent study, P sorption isotherms for the reduced system were developed for four P-deficient lowland rice soils in the Philippines, and the external P requirement of rice was found to be 0.07-0.09 ppm (43).

Again, simple methods for characterizing the P status of wetland soils in the reduced condition are essential to their proper characterization and should be used in classification.

A single lowland rice crop of IR36 that produced 9.8 t/ha contained 218 kg N, 31 kg P, and 258 kg K/ha (14). Most rice-growing soils in the Philippines are geologically young and release considerable K from weathering of primary minerals. Flooding and puddling of the soil during lowland preparation may considerably increase the soil solution concentration of K because of displacement of exchangeable K by the large amounts of Fe^{2+} and Mn^{2+} in the soil solution (39). Nevertheless, under continuous cropping with modern rice varieties, K response is becoming increasingly apparent in many lowland soils (12). Subsequent data (13) from a number of rice-growing countries in South and Southeast Asia have shown similar K responses under intensive cropping. Several soil and plant diagnostic techniques that help to identify the K requirements of rice are available. Wanasuria et al (46, 47), for instance, have shown that the electro-ultrafiltration technique for determining K status in lowland rice soils relates well to field K response.

Soil properties, duration of submergence, and temperature strongly influence the concentration of Ca, Mg, and SO_4^{2-} as well as K in the soil solution. A deficiency of Ca in rice results in discoloration of new leaves and deformation of leaf tips. Calcium deficiency is rarely seen on lowland rice plants in the field because most Inceptisols and Entisols are rich in Ca and Mg, and even in Ultisol and Oxisol areas irrigation water may supply them in sufficient amounts.

Sulfur deficiency has been reported in Bangladesh, Brazil, Burma, India, Indonesia, Nigeria, the Philippines, and Thailand (26). The reduction of SO_4^{2-} in flooded soils has three implications for rice culture: the S supply may become insufficient, Zn and Cu may be immobilized, and H_2S toxicity may arise, particularly

in soils low in Fe (38). The relation of S deficiency to soil organic matter states and redox conditions has still to be adequately established for wetland soils.

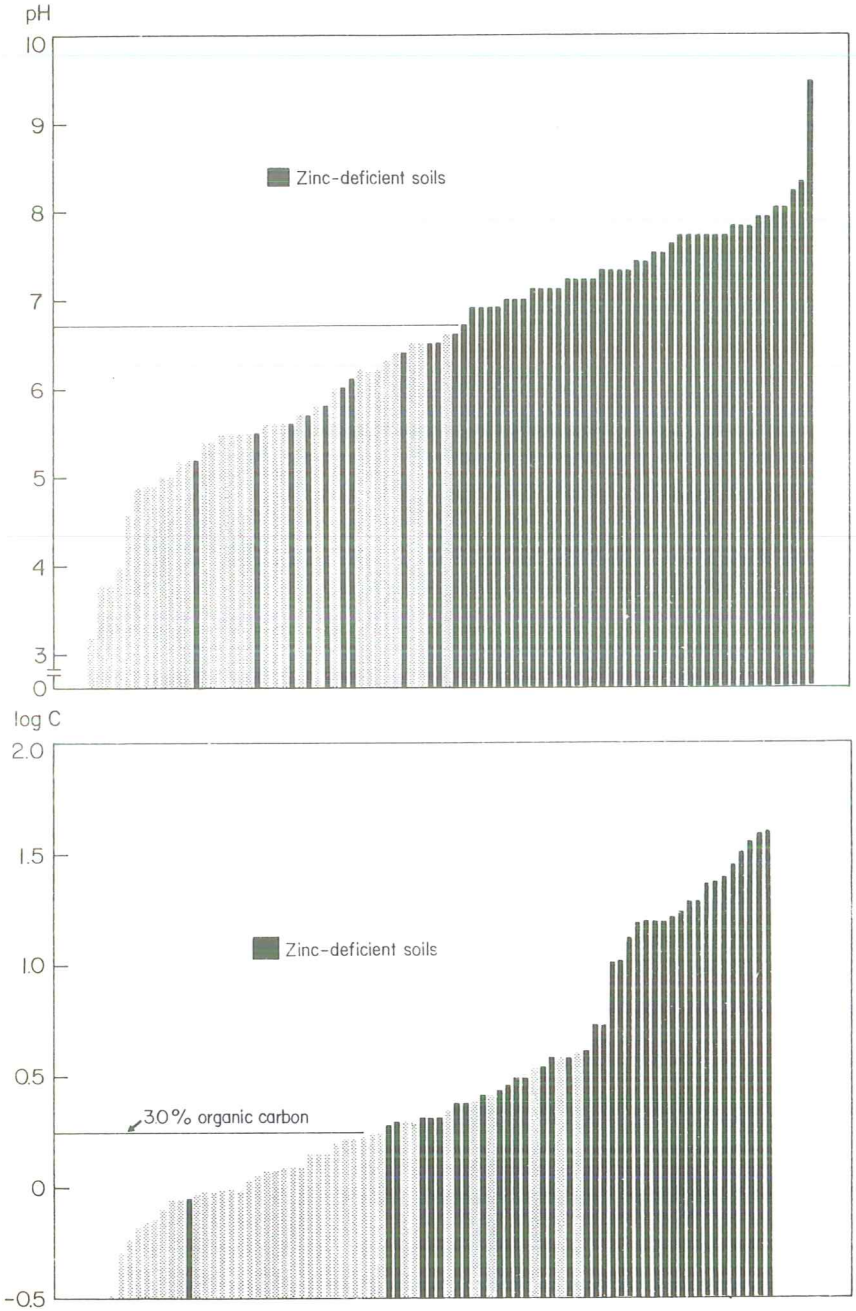
A wide variety of chemical reactions in soils undoubtedly influences the availability of Zn to rice and contributes to its widespread deficiency in wetland conditions (31). For example, high Mn concentrations antagonize Zn absorption and translocation. Calcium and Mg may also affect Zn uptake, but to a lesser extent. Zinc is most frequently deficient in alkaline conditions and in soils containing more than 3% C (Fig. 4; 21). The reversible pH change of the flooded soil, where the pH tends to increase in acid soils and decrease in alkaline soils, undoubtedly alters the Zn equilibrium concentration in the soil solution. Thus, among the factors affecting Zn availability to rice are flooding period, organic matter level, pH, and Eh (26, 27, 30).

Although the amount of Zn required by a rice crop is low (less than 1 kg/ha), Zn must be supplied to Zn-deficient soils if a high yield, or sometimes if any yield, is to be obtained. Zinc response has been recorded from many rice-growing countries of the world, although in some trials, significant but negative responses (-0.8 t/ha) to Zn have been recorded (S. K. De Datta, unpubl.); and when adequate Zn is present, negative responses of as much as 1.8 t/ha have also been found in INSFFER trials (23). Varietal differences may explain some of these results; however, improvements are needed to diagnose Zn deficiency better and relate it to soil characteristics.

STRUCTURAL CONSTRAINTS

The structural constraints to rice production differ markedly from those that apply to crops grown in unsaturated soils. Thus the process of puddling the soil -- cultivating it in the wet condition by plow or harrow -- is precisely the form of manipulation considered most detrimental for upland crops (18). Nevertheless, puddling has been shown many times to have a favorable effect on rice yields and to minimize water percolation (17, 42, 48).

The puddling process destroys the larger, transmission pores, and replaces them by increasing the number of storage and residual pores (<0.5 μm). The net effect is normally an overall increase in soil porosity because the volume of fine pores created exceeds that of the coarse pores destroyed. When dried, the clods produced will normally be larger and denser than those formed when a nonpuddled soil is dried (19), and puddled soils are often misleadingly described as compacted. In some soils, clay dispersion and trans-



4. Zinc-deficient soils in 1981 tests are concentrated at the higher pH and organic matter contents. Note the pH line at 6.8 and the carbon line at 3%.

location are induced, thus leading to the formation of a horizon of clay accumulation and low permeability immediately below the cultivation layer. This artifi-

cially induced pan is a common feature of most soils used repeatedly for rice production (33), at least those in which 2:1 layer lattice silicate clays are dominant. It is not necessarily formed in soils with low activity clays dominated by kaolinite and hydrous oxides. Such soils are less commonly used for rice production; where they are so used much greater effort is normally exercised to "puddle" them and so reduce the water use.

The fine porosity produced by the puddling process would normally be unsuitable for root growth. However, the low strength of any saturated soil means that root proliferation for rice is not impeded as long as the water content is maintained. Furthermore, the continuum of saturated pores and the free proliferation of roots help to ensure that there is little impedance to the diffusion of nutrient ions to roots. The deeper penetration of roots through the pan, especially where the saturated surface layer overlies an unsaturated horizon, may well be restricted. The importance of this will differ considerably among soils, depending on hydrology as well as inherent properties.

While puddling is thus advantageous for the rice crop, in most soils it will create a highly unsuitable condition for any crop to be grown after rice. However certain soils are resistant to dispersion, or on drying the shrinkage properties are such that a granular aggregated structure is formed (19). Few soil classification systems give significance to this "subplastic" property, although its importance in relation to the agricultural use of heavy clays in Australia has been recognized for many years (5). Attempts to determine the specific soil properties related to this behavior have not been wholly successful (2, 4, 6, 29, 35, 45).

In relation to crop production, the process of clay migration and differences in clay content between surface and subsurface are at least as important in wetland soils as in dryland soils and therefore should have an important place in relation to the classification of wetland soils.

In developing a classification system that reflects the suitability of wetland soils for use in rice-based cropping systems, it will be important to take into account the ease of puddling and the redevelopment of an aggregated condition. The simple structural classification system of Emerson (15) might well be modified to assist in any such classification scheme.

OTHER CONSTRAINTS

Salinity is an important constraint to rice production in many coastal lowlands as well as in some poorly

drained inland areas. Many acid sulfate soils of the wetlands are used to grow rice, and the potential of the many thousands of hectares of tropical peatlands in Indonesia, Malaysia, and elsewhere needs to be established. The constraints that limit rice production on such soils are similar to those that affect upland crops grown on such soils.

The removal of physical constraints to rice crop production may or may not be economic for the individual farmer. The farmer is also subject to constraints stemming from the availability and cost of credit, access to markets in order to purchase inputs as well as to sell the produce, and competing demands on time and resources (Fig. 1). Nevertheless, we may expect a better system for characterizing and classifying soils to make a material contribution to the farmer's success in rice production, and to assist in the development of better management techniques that may help ameliorate the other constraints.

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INSFFER AND THE MANAGEMENT OF WETLAND SOILS FOR GREATER RICE PRODUCTION

C. P. MAMARIL, R. B. DIAMOND, and P. J. STANGEL

The International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) was established in 1976 to investigate ways of increasing the efficiency of fertilizer use in rice under varying environmental conditions and to improve and maintain the fertility of rice soils. Various national programs, IRRI, and the International Fertilizer Development Center (IFDC) collaborate in the network, which has three major activities: research trials, training, and site tours.

Eight sets of trials are being undertaken by 59 collaborating scientists at 99 sites in 17 countries. Generally, deep placement of urea supergranules and broadcast and incorporation of S-coated urea produced higher yield than best split application of prilled urea in irrigated and rainfed lowland rice. However, this was not consistent at all sites. A complete cover of azolla incorporated before transplanting rice produced yields equivalent to those produced by urea at 30 kg N/ha. The amount of azolla biomass incorporated was correlated with grain yield. Reactive phosphate rock produced a yield response similar to that produced by superphosphate in irrigated lowland rice. Residual effects were observed even five crop seasons after the last crop that had received P application. Nitrogen remained the most limiting nutrient in most of the long-term fertility trials even after 8-15 seasons of fertilization. Applications of NP or NK tended to show additional response over N alone, suggesting that the other two nutrients may also be limiting.

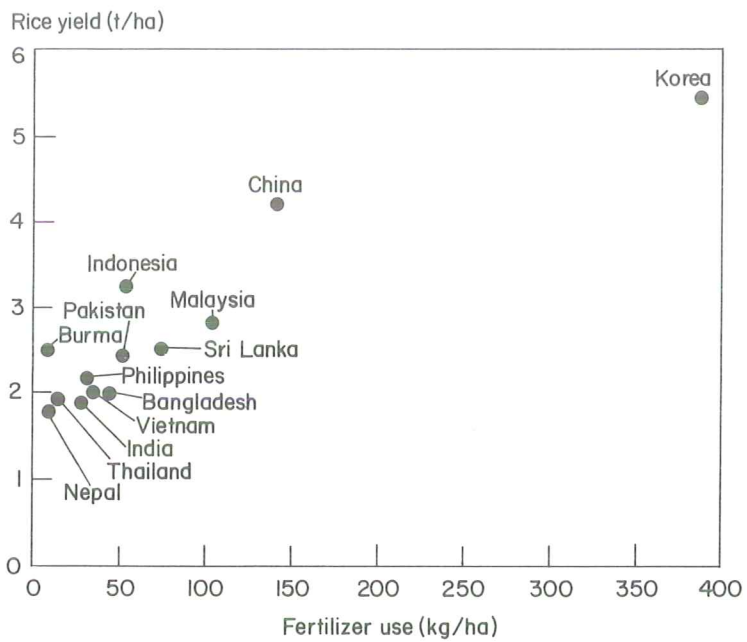
Future activities of INSFFER are discussed, with emphasis on site characterization, testing of new products such as

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partially acidulated phosphate rock, fertilizer efficiency trials under rainfed upland and drought-prone rainfed lowland rice, and economic evaluation of fertilizer products and management systems.

The consumption of chemical fertilizers in the rice-growing countries of Asia has increased considerably during the last decade. The average annual growth in total fertilizer consumption of 12 countries in the region, excluding Japan, between 1960 and 1982 ranged from 4 to 17%, or an average of 10% per year (1). This, together with the development and dissemination of fertilizer-responsive rice varieties as well as new technologies in rice culture, has brought about a remarkable increase in production in most rice-growing countries. As shown in Figure 1, the rice yield in most of these countries is related to the amount of fertilizer applied per hectare. Since the cost of this input tends to increase as a result of the increasing price of oil, a nonrenewable raw material, there is some concern that farmers may soon be reluctant to apply the necessary amount of fertilizer to attain profitable yield levels. Consequently, recent research activities have been focused on increasing fertilizer-use efficiency in rice.

The establishment of the International Network on Soil Fertility and Fertilizer Evaluation for Rice



1. Average fertilizer use per hectare and rice yields, 1979-81 (2).

(INSFFER) in 1976 was one of the manifestations of concern among IRRI, IFDC, and national scientists involved in studying soil fertility and fertilizer management in rice. The main objectives of the Network are to find ways and means of increasing fertilizer-use efficiency and to improve and maintain soil fertility levels that will increase and stabilize rice productivity at reasonable levels.

THE INTERNATIONAL NETWORK ON SOIL FERTILITY AND FERTILIZER EVALUATION FOR RICE

Historical background

INSFFER was conceived and informally organized in 1975 but was formally established a year later. Ten countries joined the Network, which in the first year was named the International Network on Rice Fertilizer Efficiency (INRFE). The name was changed to the International Network on Fertilizer Efficiency in Rice (INFER) after the first year, and in 1979 the present name was adopted to include research on soil fertility and biological N fixation as well as training.

The number of member countries has grown to 17, but some do not participate regularly. The current countries and the number of collaborating scientists are given in Table 1. Egypt, Mali, Sierra Leone, and the Republic of Korea joined in the past but ceased to participate. The number of sites grew from 27 in 1976 to 99 in 1983.

Table 1. Number of collaborators from the 17 INSFFER members participating in the 1983 research trials.

Member	Collaborators (no.)
Bangladesh	1
Burma	3
Cameroon	1
China	2
India	26
Indonesia	7
Malaysia	1
Nepal	1
Nigeria	1
Pakistan	2
Panama	1
Philippines	4
Senegal	1
Sri Lanka	2
Taiwan, China	1
Thailand	1
Vietnam	4
Total	59

Components of the Network

The activities of the Network are 1) collaborative research trials, 2) training, and 3) site visit tours.

The research trials are formulated by collaborating scientists during the annual International Rice Research Conference (IRRC) or during the workshop that precedes or follows a site visit tour. These research trials are conducted by the collaborating scientists, who provide their own logistics; thus the trials are part of their national programs. IRRI and IFDC provide technical coordination. IRRI supplies some needed materials such as azolla and fertilizer applicators, undertakes soil analyses and occasionally plant analyses, collates and analyzes data from collaborators, and prepares field books and reports. IFDC provides new fertilizers to be tested. A field book is prepared for each trial describing the different treatments, operations to undertake, and information and agronomic data to collect.

Recognizing the need for appropriately trained manpower to assist in the conduct of the trials, the Network decided to institute a training course to strengthen the capabilities of researchers and technicians participating in the INSFFER program in the theoretical and practical aspects of soil fertility, fertilizer use, biological N fixation, and experimental techniques. The 4-month training course was first offered in 1979 and has been subsequently conducted once a year. As of 1983, a total of 106 representatives of 63 organizations from 14 countries had participated in the course. Currently, there are 26 participants from 23 organizations in 12 countries. The course involves classroom, laboratory, and field activities. Field trips to soil fertility and fertilizer experiments in farmers' fields are part of the participants' activities. Subjects ranging from experimental design, different aspects of soils, fertilizers and their management, statistical analyses, and the rice plant and its environmental requirements to report writing and related disciplines are discussed in the classroom. Practical training in photography is also given. The trainees analyze statistical results of their field experiments and prepare a report. Each trainee is required to present a scientific seminar toward the end of the course.

Five site visit tours -- to Bangladesh; Taiwan, China; India; Indonesia; and Vietnam -- have been undertaken since 1980. The objectives of the site visit tours are

- to observe and characterize sites of INSFFER trials,
- to observe soil problems and soil fertility management practices in the areas visited,

- to exchange information among tour participants and local scientists, and
- to discuss future directions of research on soil fertility and fertilizer management in rice.

In most of the tours, participants were not only INSFFER collaborators and IRRI and IFDC scientists, but also scientists from the host countries, national research organizations, fertilizer companies, and other foreign research institutions. Sixteen INSFFER collaborators from nine countries participated in the 1983 tour in Indonesia, which was the largest among the five tours so far undertaken. After the tour, a 2-day workshop was held.

THE COLLABORATIVE TRIALS

Collaborative trials can help alleviate the problem of limited resources for research among the developing rice-growing countries. Various agroecological conditions may exist within a country; if the resources of the country cannot cover all these conditions, results of trials from another country with similar conditions may be of use. It is, however, essential that sites for all trials, not only the soil but also the prevailing environmental conditions during the experiment, be characterized so that results can be translated from one country to another. INSFFER also provides the opportunity to identify site parameters that influence effectiveness of potentially viable fertilizer management practices. Thus recommendations to farmers can be further refined.

The treatments included in each trial are proposed by collaborators on the basis of previous research findings obtained by the national research program, IRRI, and IFDC. Subsequently, the kinds of observations to be made are also agreed upon by the group.

The following are the collaborative trials agreed upon in 1983:

- nitrogen fertilizer efficiency in rice under irrigated lowland, rainfed lowland, and deepwater conditions;
- azolla use in rice;
- long-term fertility trial;
- phosphorus sources for lowland rice;
- lowland acid soil nursery;
- comparison of hand- and machine-applied N fertilizer in irrigated lowland rice; and
- integrated use of inorganic and organic N sources in irrigated lowland rice.

The N fertilizer efficiency in irrigated lowland rice was the first of a series of five collaborative trials conducted. It started with the comparison of

prilled urea (PU) applied either as best split, liquid band placement, or mudball; urea briquets applied point placed at depth; and sulfur-coated urea (SCU) applied broadcast and incorporated as basal dressing. During the fourth and fifth trials of N fertilizer efficiency in irrigated lowland rice, prilled urea applied best split, SCU applied broadcast and incorporated, and urea supergranules (USG) deep point placed were compared at several N rates.

In the rainfed lowland rice trials, PU, SCU, and USG were likewise compared at different N rates. The current trial is the third in the series; the first was conducted in 1978.

The N fertilizer efficiency in deepwater rice was first investigated in 1980. Prilled urea applied split or in combination with foliar application of urea solution or in combination with SCU was compared with SCU broadcast and incorporated in combination with PU solution foliar-applied as well as deep placed USG. The current trial compares PU, SCU, and USG at three levels of N, and collaborators can choose between the improved variety RD19 or their local variety. Prilled urea is applied either all basal, broadcast and incorporated, or 2/3 basal broadcast and incorporated followed by 1/3 foliar-applied urea solution at 5-7 days before panicle initiation.

An azolla trial in irrigated lowland rice was started in 1979. The main objective was to determine the contribution of azolla incorporated either before or after transplanting to grain yield under various environments. Azolla use was compared with urea at two N rates of a combination of azolla and urea. In the third trial, plant spacing was introduced as a variable to determine if it has any influence on the growth of azolla and subsequently on grain yield of the rice crop.

The trial on sources of P in flooded rice was started in 1977 with the objective of evaluating phosphate rocks for agronomic and economic effectiveness in flooded rice in selected rice soils and environments. Phosphate rock is compared with commercially available P fertilizers such as ordinary superphosphate or triple superphosphate and locally indigeneous P sources such as guano at varying P levels. Five consecutive rice crops received these P sources; they were followed by several rice crops without the addition of P to determine the residual effects of the materials compared. Unfortunately, some initial sites were not P responsive and had to be discontinued.

To monitor soil fertility changes under continuous fertilizer application and intensive cropping under irrigated lowland rice, the long-term fertility trial was formulated and started in 1976. The treatments consist of a single application of the three fertilizer

nutrients NPK, combinations of any two nutrients, and the combination of all three nutrients. At some sites where other nutrients such as Zn or S may be limiting, these were included as optional treatments.

The acid lowland soil nursery, which was started in 1981, is a joint undertaking of the International Rice Testing Program (IRTP) and INSFFER, having as its primary objective the identification of rices that can tolerate strongly acidic conditions with or without minimum amendments. The amendments include P and a combination of P and lime. The initial nursery included only 10 entries, but the current (1984) nursery has 99 entries, including 3 checks, originating from several national programs.

The last two trials added were formulated in 1983. The objective of the trial on hand- versus machine-placed PU and USG is to determine the comparative agronomic and economic effectiveness of the different methods of application in irrigated lowland rice under different environmental conditions. The placement methods are compared with the farmers' practice and the researcher's best split application of urea at two rates of N.

Because of the increasing cost of inorganic fertilizers, several collaborators expressed interest in seeking appropriate alternative fertilizer sources such as biofertilizers. Likewise, participants attending the International Conference on Organic Matter and Rice in October 1982 suggested that investigations on the integrated use of organic and inorganic fertilizers in lowland rice be undertaken by the INSFFER collaborators. Consequently, a trial with the following objectives was proposed during the 1983 IRRC:

- to evaluate the effectiveness of inorganic N fertilizer applied alone or in combination with azolla or fresh straw in as many locations as possible,
- to compare best split and deep placement applied urea with or without organic fertilizers, and
- to determine the long-term effect of the integrated use of inorganic and organic fertilizers on the soil fertility status of lowland soils.

The trial is being carried out by collaborators in several countries. Some participants replaced straw with green manures.

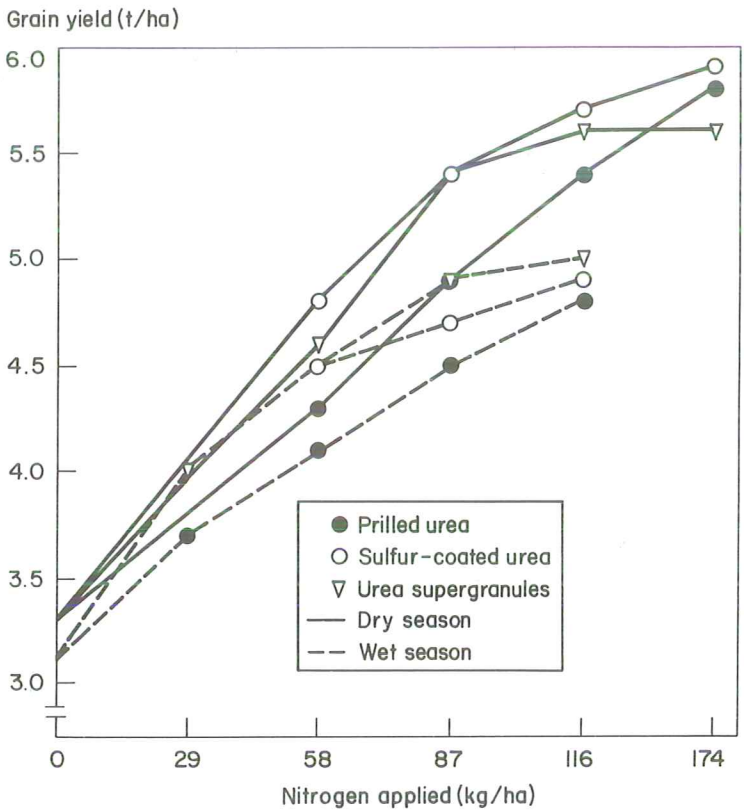
HIGHLIGHTS OF THE COLLABORATIVE TRIALS

Nitrogen fertilizer efficiency

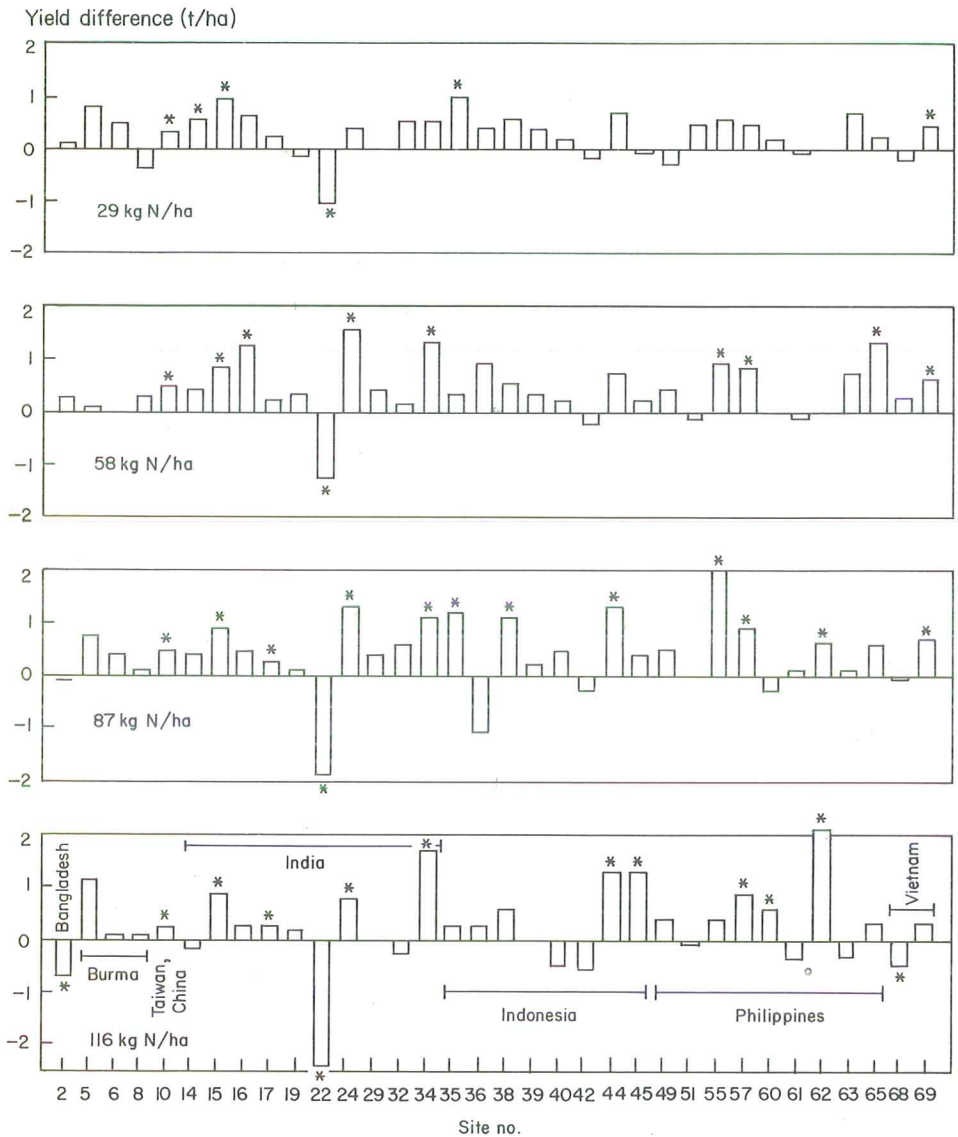
In irrigated lowland rice, deep placement of urea either in mudball, briquet, or supergranule form and slow-release SCU generally produced higher fertilizer-

use efficiency than PU applied best split (2). The advantage of deep placement and slow-release materials was more apparent at lower N rates. Beyond the rate of 87 kg N/ha, the differences among the materials were not significant (Fig. 2). In fact, in a number of sites, USG produced yields lower than those produced by PU best split.

During the dry season, the yields for SCU ranged from 0.6 t/ha less to 1.2 t/ha more than the yields for PU over all N rates, with an average 0.3 t/ha advantage of SCU over PU (2). The yields for USG ranged from 1.4 t/ha less to 1.3 t/ha more than the yields for PU; the average advantage of USG over PU was 0.2 t/ha. The average difference in yield between SCU and PU during the wet season over all N rates was 0.8 t/ha less to 1.5 t/ha more or an average 0.2 t/ha advantage of SCU over PU, while the yield difference between USG and PU was 1.7 t/ha less to 1.6 t/ha more for an average 0.3 t/ha advantage of USG over PU.



2. Nitrogen response of rice that received different forms of urea and rates of application. Data are averages of 12 dry and 34 wet season trials. The Fifth International Trial on Nitrogen Fertilizer Efficiency in Rice, INSFFER, 1982.



3. Significant increases or decreases in grain yield of 34 trials resulting from the application of nitrogen as urea supergranules deep point placed and as best split prilled urea at 4 rates. The Fifth International Trial on Nitrogen Fertilizer Efficiency in Rice, INSFFER, 1982 wet season.

While on the average the advantage of USG deep placed and SCU broadcast and incorporated over PU applied best split was quite evident, it was not consistent at all the sites (Fig. 3). The trials in Ludhiana, Punjab, India (site 22), for example, show that USG deep placed was inferior to PU applied in three equal splits. The site has a percolation rate of about 7 mm/h, loamy sand, pH 8.2 and CEC of 5 meq/100 g

soil, and is classified as Typic Ustochrept. The results obtained in the same site have been consistent for the last 3 years. It has also been observed that differences among the materials within sites are not consistent among N rates. This inconsistency could be attributed to differential floodwater depth among the plots when the basal amount of N was applied. It has been shown elsewhere that NH_3 volatilization loss is considerable when the fertilizer N like urea is applied with some standing water, even when the fertilizer is subsequently incorporated.

On the basis of the results of the third to the fifth N efficiency trials in irrigated lowland rice, and the multifertilizer response models, SCU and USG were 25-30% more input efficient than PU (J. C. Flinn, pers. comm.). The yield efficiency of SCU and USG was 1.3-1.4 higher than that of PU. Economic analysis of the same trials shows that in about half of the South and Southeast Asian INSFFER sites, the modified N sources were more profitable than PU -- even at substantially (over one-third) higher cost than the current price of N as PU. As the price of PU increases, the relative profitability of using SCU or USG deep placement increases.

On the rainfed rice trials, trends were similar to those in the irrigated rice trials (3). There were, however, relatively fewer sites where yield differences between SCU and USG over PU were negative, even at the rate of 87 kg N/ha. In fact, at that N rate there were several sites where USG yielded significantly more than PU best split.

The effect of deep placement was not as prominent in deepwater rice as in irrigated or rainfed lowland rice (4). Moreover, foliar application of urea did not produce any advantage. In the first and second sets of trials, SCU appeared to be a better source than PU either broadcast and incorporated or in combination with foliar applied urea. However, in the third set of trials USG at the medium rate of 58 kg N/ha produced a positive advantage over PU broadcast and incorporated at all five sites, but the differences were not significant. At the high rate of 116 kg N, however, USG produced yields significantly lower than PU in 2 out of 5 sites.

The inconsistencies among sites suggest that there are environmental parameters as well as management factors that influence the effectiveness of the modified urea forms. Thus it is imperative that these parameters be identified so that recommendations regarding fertilizer management can be tuned according to conditions prevailing in the farmers' fields.

Azolla use in rice

At most of the sites where the azolla trial was con-

ducted, yield benefits were positive when azolla was applied alone or in combination with urea N (Table 2, 3). Azolla inoculated and subsequently incorporated before transplanting appears more effective than azolla grown after transplanting (5). Azolla incorporated before transplanting plus 30 kg N applied in three splits gave yields equivalent to those from 60 kg N/ha from urea. Yields were lower when azolla was grown and incorporated after transplanting, probably because of the lower biomass produced by azolla grown simultaneously with the rice crop (Fig. 4). However, it was also observed that the planting distance of the rice crop did not affect grain yield, suggesting that distance could not have affected the growth of azolla grown together with the rice crop.

Although the effect of azolla is quite encouraging, additional work -- including a study of the eco-

Table 2. Effect of azolla application on rice yield, INSFFER first and second trials.

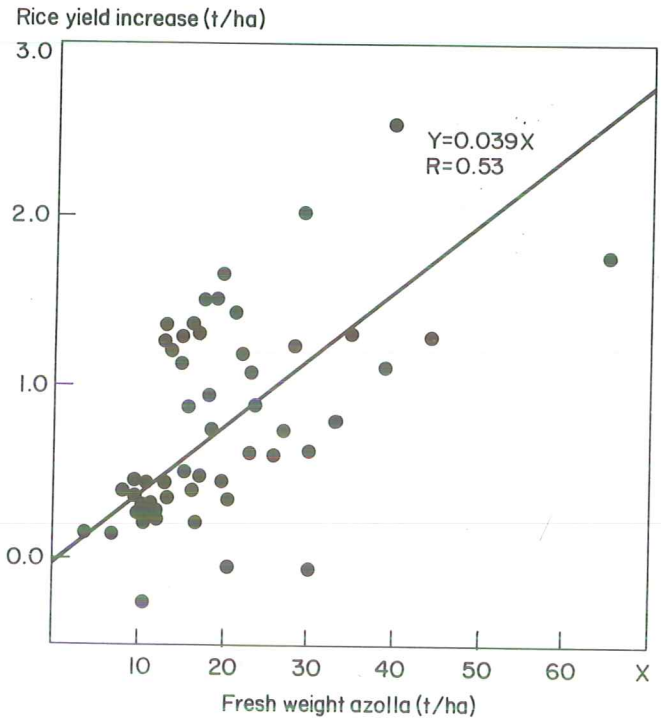
Treatment[a]	Yield (t/ha)		Mean
	1979 (12 sites)	1980 (17 sites)	
1. Control, zero N	2.5	3.4	3.0 (100)
2. 30 kg N	3.2	4.0	3.6 (120)
3. 60 kg N	3.7	4.4	4.0 (133)
4. Azolla (IBT)	3.2	4.2	3.7 (123)
5. Azolla (inoculated and IAT)	3.1	4.2	3.6 (120)
6. Same as #5 (unincorporated)	2.9	4.1	3.5 (117)
7. Same as #4 + 30 kg N	3.7	4.5	4.1 (137)
8. Same as #5 + 30 kg N	3.5	4.5	4.0 (133)
9. Azolla (GB&AT and incorporated)	3.8	4.5	4.2 (140)

[a]IBT = incorporated before transplanting, IAT = incorporated after transplanting, GB&AT = grown before and after transplanting.

Table 3. Effect of azolla application on rice yields, INSFFER third and fourth trials.

Treatment[a]	Planting distance[b]	Grain yield (t/ha)		Mean
		1981 (13 trials)	1982 (18 trials)	
No N, no Azolla	A	2.73	2.89	2.82
60 kg N/ha	A	3.81	4.14	4.00
60 kg N/ha	B	3.75	4.27	4.05
Azolla (IBT) + 30 kg N	A	3.83	4.17	4.03
Azolla (IBT) + 30 kg N	B	3.91	4.15	4.04
Azolla (GB&AT and incorporated)	A	3.58	3.93	3.78
Azolla (GB&AT and incorporated)	B	3.68	4.13	3.94
Azolla (G2XAT)		3.62	3.87	3.76

[a]IBT = incorporated before transplanting, GB&AT = grown before and after transplanting, G2XAT = grown twice after transplanting. [b]A = 20 X 20 cm, B = 10 X 40 cm.



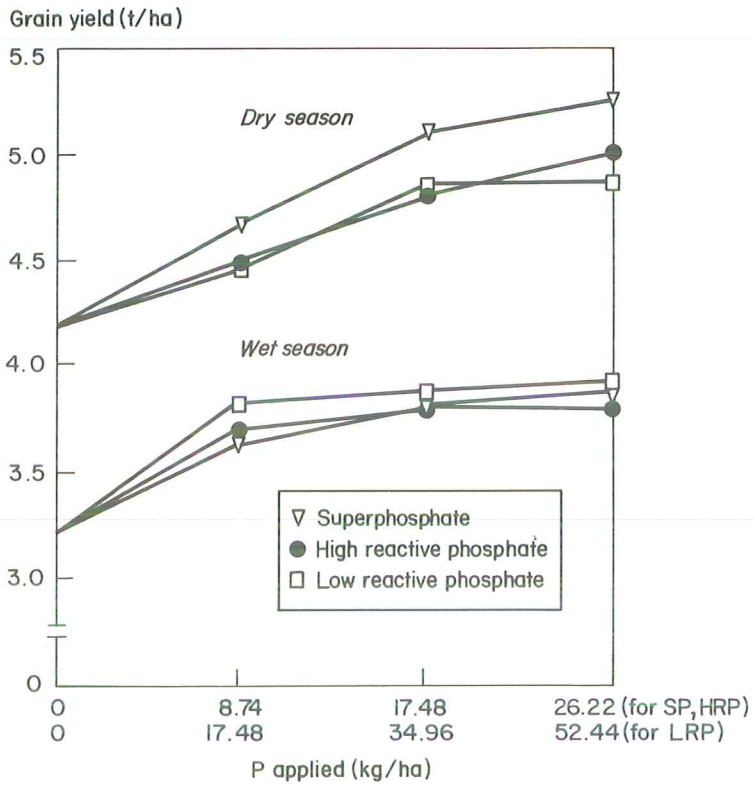
4. Relation between rice yield increase and fresh weight of azolla incorporated, INSFFER, 1981.

nomics of azolla application and resolution of some of the constraints encountered in growing azolla such as pests, diseases, and nutritional problems -- needs to be done. Successful use of azolla requires good water control throughout the season, an adequate supply of available soil P, and insect-free conditions.

Sources of phosphorus in flooded rice

On the average, an increase of more than 0.5 t/ha was obtained from all P sources tested, namely, superphosphate, highly reactive phosphate rock, and indigenous local phosphate rock or guano (6). The P response was higher during the dry season than during the wet (Fig. 5). Yield responses were greater from superphosphate than from the less soluble P sources during the dry season, but there were no differences among the sources during the wet season.

Residual effects after five seasons of continuous application of P were obtained at four sites. The average yield increases due to residual P from all sources were 1.5 t/ha during the dry season and 0.8 t/ha during the wet.



5. Average yield response of rice in 82 P responsive trials to different P sources. International Trial on Sources of Phosphorus in Flooded Rice, INSFFER, 1983.

Long-term fertility trial

The results of 80 trials from 11 sites in 7 countries have been reported since 1977 (7). More than 70% of the trials gave significant response to N alone with an average yield increase of 1.5 t/ha for the dry season trials and 1.2 t/ha for the wet season. Only 25% of the trials gave a yield response to P alone, with an average yield increase of 0.9 t/ha, and 16% of the sites showed a response to K alone, with an average yield increase of 0.8 t/ha. Some of the trials produced yield responses to NP, PK, and NK, but not to the individual nutrients alone, suggesting that any two elements might be equally limiting. Only four of the sites -- two in Indonesia and two in the Philippines -- are continuing. At one of the Indonesian sites, Lanrang, N and P alone gave significant yield responses after 10 croppings, and the addition of Zn to NPK tended to depress yield, especially during the dry season. Only N remains limiting after eight croppings at the other site in Indo-

nesia. Likewise, at the Tanay site in the Philippines, N is definitely limiting while P is beginning to be apparently deficient after 13 croppings. The combination of N and P further increases yield over N or P alone. Nitrogen remains the limiting nutrient at the Luisiana site even after 15 cropping seasons. In general, yields and yield responses to limiting nutrients were greater during the dry season than during the wet.

FUTURE ACTIVITIES AND STRATEGIES OF INSFFER

It is apparent from the highlights of past experiments that there is a need to sort out the reasons for the inconsistencies observed among sites regarding the various methods of N fertilizer application. Thorough site characterization and monitoring of essential parameters that could influence the efficiency of applied fertilizers should be carried out. Results could also be extrapolated for other sites with similar agroecological conditions with greater confidence if this is done. Recognizing that inadequate facilities and lack of properly trained manpower are constraints at some INSFFER sites, intensive site characterization and monitoring of essential parameters will be carried out at a few representative sites in each participating country.

Fertilizer efficiency trials in upland rice should be undertaken to increase its yield.

The integrated use of inorganic and organic fertilizers should be continued, not only for irrigated lowland but also for rainfed lowland and upland conditions. This is important in countries where inorganic fertilizers are primarily imported and yet indigenous biofertilizers may abound.

Partially acidulated phosphate rock (PAPR) should be tested since it reduces the sulfuric acid requirement and also allows the use of unreactive local phosphate rock (PR), which lacks the potential for direct application or use in a large-scale conventional commercial operation. Use of PAPR would also save energy.

Deep placement of N and K to increase soil fertility and increase the amount of water available to upland crops or rainfed rice grown in drought-prone areas should be investigated.

Basic fertilizer efficiency work should also be conducted at sites where detailed characterization is undertaken.

The efficiency of various fertilizers used under varying cropping intensities needs to be measured.

It is anticipated that, as the intensity of cropping increases, other nutrient problems such as

those associated with S and Zn will emerge. Deficiencies of these elements have already been reported in a number of countries, and to enable scientists to share their experiences, the INSFFER program should incorporate collaborative research on these elements.

To ensure the adoption by farmers of the fertilizer and fertilizer management technologies developed, the economic evaluation of fertilizer products and management systems will be given a higher priority.

In areas where INSFFER and other international networks at IRRI, IFDC, and other centers have something in common, closer collaboration should be established to minimize duplication and lighten the burden on national program scientists.

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PROBLEMS IN CHARACTERIZING AND CLASSIFYING WETLAND SOILS

F. R. MOORMANN and H. T. J. VAN DE WETERING

Soil taxonomy at present uses the aquic moisture regime in various ways, the definition being sometimes ambiguous. No distinction is made between soils that are saturated and reducing throughout (groundwater gley soils) and soils in which only the upper horizons are temporarily water saturated.

For a revision of the definition of the aquic moisture regime, the terminology of the new Soil survey manual is proposed. The aquic moisture regime can be defined in terms of classes of depth to the wet state, classes of duration of the wet state, and, eventually, degrees of reduction of the soil. The lack of precise and generally valid relationships between soil morphological characteristics and the dynamics of free soil water is discussed.

Specific characteristics of paddy soils occurring on lands that are submerged during the cool growing season are related to Soil taxonomy.

The generic term "wetland" readily conveys the notion of an excess of water on the land during part or all of the year. "Wetland soils" can thus be defined as soils whose development and properties are strongly influenced by temporary or permanent saturation in the upper part of the pedon. The waterlogging of the surficial horizons brings about reducing conditions for periods long enough for temporary chemical and physical changes to take place. In most cases, such temporary changes will impose permanent characteristics on the soil for which the term "gley-phenomena" is commonly used. The term wetland soils, as used here, refers to soils having an aquic moisture regime, as defined in Soil taxonomy, pp. 54-55 (15).

In order to use the aquic regime for differentiation at the highest categories of the classification,

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the whole soil must be saturated and reduced. Such soils are certainly wetland soils as earlier defined. Soil taxonomy, however, also assigns an aquic moisture regime to pedons in which only the lower horizons are saturated. This "lesser-grade" wetness is recognized as a diagnostic feature at a much lower level of generalization, that of the subgroup level. Normally, the term "wetland soil" would not be used for such pedons, but no firm rules can be cited in this respect.

As we will discuss in this paper, many classification systems distinguish between surface-water gley soils (c.f. 14) and groundwater gley soils. In surface-water gley soils, water stagnating on less permeable or nonpermeable layers causes the surface horizons to be temporarily (or even permanently) reduced, without matching wetness in the deeper horizons. Our working definition of wetland soils would encompass such surface-water or pseudogley soils.

Strictly speaking, such soils do not have an aquic moisture regime, as defined in Soil taxonomy. On p. 54 it is stated that for an aquic moisture regime recognized in the highest categories, the whole soil must be saturated (our emphasis). Another requirement is that a soil be considered saturated if the groundwater in an unlined borehole stands at or very close to the surface. In surface-water gley soils, a borehole that penetrates below the impermeable layer will rarely if ever be filled with water.

Even though many surface-water gley soils may not have an aquic moisture regime, as defined in Soil taxonomy, we will consider them in this presentation as wetland soils.

In this paper, we will enumerate some of the problems the taxonomist meets when trying to incorporate the characteristics indicating "wetness" or hydromorphism into a taxonomic soil classification system.

EXCESS WATER IN WETLAND SOILS: THE AQUIC MOISTURE REGIME

In Soil taxonomy the actual moisture regime in soils is introduced as a diagnostic property. To be recognized as wet or hydromorphic, the soil should be wet and the conditions reducing throughout. This, however, is not an absolute criterion in Soil taxonomy, because the definition of aquic suborders includes artificially drained soils. Consider, for instance, the definition of Aqualfs: They are Alfisols that have an aquic moisture regime or are artificially drained and that have characteristics associated with wetness (our emphasis). Clearly, this definition implies that Aqualfs do not have to have an aquic moisture regime at present, as long as they have been formed under wet

conditions "some time in their history." Drained lake bottoms and reclaimed marine and riverine wetlands, commonly known as polders, often have soils that, because of artificial drainage, are no longer water saturated and reducing. Should such soils, even with appropriate morphological wetland features, be considered wetland soils? We know that they are not at present water saturated for extended periods. Under such conditions, is it correct to classify them in the aquic suborders?

If the answer to these questions is affirmative, we also should consider the reverse condition, namely, that of soils which under natural conditions are well drained, but in which, because of basin irrigation, the conditions required for an aquic moisture regime may be fulfilled. One can ask if such artificial wetland soils should be distinguished at a high level of our taxonomic classification system, namely that of the suborder level. The trend is to key such well-drained soils with an imposed surficial aquic regime (mainly so-called "paddy soils") at a lower level, that of the subgroup (8).

The crucial question then arises: Can the aquic soil moisture regime, as expressed by waterlogging and reducing conditions, be used as a firmly established diagnostic property in a taxonomic system? These writers contend that it may be used, but that we simply lack the data to do so in an unequivocal fashion.

SOIL WETNESS CHARACTERIZATION: WATER TABLE CHANGES

In the new Soil survey manual (Chapter 4, Directive 430-V-SSM, May 1981 OSDA-SCs -- limited edition) classes of soil wetness are introduced for the examination and description of soils in the field. Such classes, enumerated below, are based on systematic measurement of zones of wetness, whereby wet soil material is defined as containing (free) water at a tension of 1 kPa (0.01 bar) or less. The following are the classes of depth to the wet state:

- Class 1 -- not wet above a depth of 150 cm.
- Class 2 -- wet in some part above a depth of 150 cm but not above a depth of 100 cm.
- Class 3 -- wet in some part above a depth of 100 cm but not above a depth of 50 cm.
- Class 4 -- wet in some part above a depth of 50 cm but not above a depth of 25 cm.
- Class 5 -- wet above a depth of 25 cm.

These classes are based on soils that are not irrigated and not frozen in any part.

In the description, moreover, the duration of the wet state is taken into account. The classes of duration of the wet state are:

- Class a -- wet less than one-twelfth of the time.
- Class b -- wet one-twelfth to one-fourth of the time.
- Class c -- wet one-fourth to one-half of the time.
- Class d -- wet more than half of the time.

Most wetland soils would belong to Class 5, but under certain conditions Class 4 soils would probably also have an aquic moisture regime recognized at the suborder level. The duration classes are much less easily linked with the soil moisture regime.

A third characteristic of the wet state is the movement -- vertical or lateral, or both -- of the saturating water. The net movement determines the transport of solutes. A net movement down causes leaching of soil components. A net movement up causes accumulation. This characteristic of the wet state is very difficult to quantify, but its long-term effect on soil properties can be measured. For instance, strong leaching can remove those components that normally characterize gley phenomena.

The depth of the water table in soils is a property that may or may not be related to the morphology of the soil horizons. In the case of artificially drained soils, the moisture regime may have changed from aquic to nonaquic, even though the aquic morphogenetic characteristics remain, at least for many years. In terms of Soil taxonomy this means that morphogenetic characteristics of wetness and the depth to the groundwater table become independently variable soil properties. This has led various soil survey institutes to use the variation in depth to the water table during the year as a separate parameter in the legend of soil maps.

In the Netherlands, water table classes are based on the average seasonal fluctuation of the water table (16). This fluctuation is calculated from one-third of the sum of the highest three water tables per year (April to April) and one-third of the sum of the lowest three water tables per year, averaged over n years. For the Netherlands, where annual precipitation varies considerably, the minimum value of n is 8 years. The main water table classes used in the Dutch system are shown in Table 1.

The system in West Germany is comparable (1); it is based on the average fluctuation below the level of the soil surface, with special symbols for artificially lowered water tables. Moreover, three classes of surface-water gley are recognized (weak moderate, and strong), and one class of "Hangnaesse," probably best translated as "seepage wetness."

For tropical conditions (Typic Tropustic, Isohyperthermic), a similar determination of groundwater

Table 1. Main water table classes in the Netherlands (udic, mesic).

Water table class	Water table (cm below surface)	
	Mean highest	Mean lowest
I	–	<50
II	–	50-80
III	<40	80-120
IV	>40	80-120
V	<40	>120
VI	40-80	>120
VII	>80	>120

classes was carried out by Veldkamp (17) in lowland valleys and adjacent uplands at the International Institute of Tropical Agriculture, Ibadan, Nigeria. Even though no artificial drainage was applied, there was no clear relation between the groundwater class and the morphometric indications for wetness such as gray matrix colors.

The lack of a one-to-one relationship between the actual dynamics of groundwater (including superficial groundwater) and soil characteristics has several causes, of which we give a few examples:

- Artificial drainage changes the aquic moisture regime, as defined in Soil taxonomy, to a non-aquic moisture regime. Most (but not all) morphometric properties that are commonly related to wetness (mottling, low chroma colors) will change in time because of biotic homogenization and further weathering. However, such changes are slow, and clayey wetland soils in temperate zones retain their grayish, low chroma colors for several centuries. Only in coarser textured soils may the morphogenetic characteristics of wetness disappear in a few decades upon drainage, thus establishing a better relationship with the actual drainage condition of the soil.
- Groundwater measured to determine water table class may contain considerable dissolved O_2. Thus, soils may appear temporarily wet or very wet when the depth of groundwater is monitored in open holes or in groundwater tubes. Yet at the same time no morphometric signs of wetness are found. This is a rather common situation in most ustic tropical areas, especially in conditions of moderate relief and lateral (oblique) water movement (17). Comparable conditions were noted in Germany (11) and elsewhere.
- The environment may be such that reduction is negligible, even after long periods of saturation with stagnant water. The example given in Soil taxonomy (p. 54) is of the cold climatic

zones with a temperature of less than 1°C (average). Other examples are the very saline waterlogged soils of deserts, where salinity interferes with the growth of reducing micro-organisms.

- The lack of organic matter, combined with a moderate to high $CaCO_3$ content, may also restrict reduction, necessary to develop the gray colors that characterize most aquic moisture regimes. Thus, many soils under basin irrigation for rice in northwestern India do not develop the low chroma matrix colors with accompanying root mottling common in the epipedons of many rice-growing soils (9).

Determination of groundwater class, even if limited to a few selected wetlands, is usually a costly undertaking. In most tropical countries such determinations can, for all practical purposes, be undertaken only in and around established agricultural stations, but at present no means and personnel are available for carrying out such activities on a large scale.

We conclude that, while measuring depth of groundwater over time provides useful data, such data by themselves cannot be used as a taxonomic property. Groundwater/surface water measurements may be used for creating soil management phases of various taxa, and this at all categorical levels of the Soil taxonomy classification.

DURATION OF WATERLOGGING AND THE AQUIC MOISTURE REGIME

Soil taxonomy (p. 55) states, "The duration of the period that the soil must be saturated to have an aquic regime is not known." We can consider this statement from another viewpoint: Should there be a taxonomic differentiation among wetland soils based on the duration of (intense) reducing conditions?

Soil taxonomy recognizes a peraquic regime, e.g., for soils of tidal marshes, though the term is not used specifically in naming very wet taxa. The Hydraquent great group may be cited as a taxon with a peraquic moisture regime.

The duration problem becomes taxonomically important in regions where the moisture regime of well-drained upland soils is ustic or xeric, especially when the soil temperature regime is thermic or warmer (13). Here, an aquic moisture regime affecting the superficial horizons during the wet season is not operative during the dry season. In fact, unless the soil has continuous high groundwater, the soil moisture is

rapidly depleted during the dry season and the soil moisture regime subsequently approaches that of normal, well-drained soils in the ustic or xeric environment.

Measurements along a slope in an ustic, isohyperthermic regime in Ibadan, Nigeria (10), showed that the lowest member of this catena has a normal aquic moisture regime. At midslope, the contrast between the wet and the dry periods was clear, thoroughly affecting the potential and desirable management practices. Yet, on the basis of the definition of the aquic moisture regime, both members of the catena could be classified as Tropaquents.

To improve upon this situation, it is proposed that a soil moisture regime, tentatively called ustaquic, be created. In this regime, the pedon has an aquic moisture regime, but during the dry season the moisture control section is dry in some or all parts for 90 or more consecutive days in most years. Areas with an ustaquic soil moisture regime are considerable, especially in the monsoonal regions. Many soils on fluvial or marine terrace formations of South and Southeast Asia, for instance, are wet and often flooded by artificial ponding for rice growing in the rainy season but become very dry with free groundwater well below the reach of plant roots during the long dry season.

Distinction of the ustaquic soil moisture regime may be done at the subgroup level (e.g., Ustic Tropaqualf, Ustic Haplaquent).

No temperature regime limits for the ustaquic moisture regime may be required, but it is most probable that in the cooler climatic zones the moisture control section will not dry out for more than 90 consecutive days if the soil has an aquic moisture regime in the rainy portion of the year. Hence we may expect ustaquic moisture regimes in areas where the general soil moisture regime of the better drained soils is ustic or xeric and where the soil temperature regime is thermic, isothermic, or warmer.

Ustaquic moisture regimes may be expected in the orders of Alfisols, Inceptisols, Mollisols, Ultisols, and Vertisols. This moisture regime is believed to be absent in Aridisols, Histosols, and Oxisols, and to be rare in Entisols and Spodosols.

In areas where the soil moisture regime of the well-drained sites is udic, no taxonomic parallel to the proposed ustaquic moisture regime exists. Yet there are many soils which during part of the year are superficially wet, while in periods in which evaporation exceeds precipitation the level of the groundwater may be well below the solum. Such soils will mostly be surface-water gley soils (to be discussed).

A moisture regime similar to ustaquic is not needed in desert areas, where the dominant moisture

regime is aridic or torric. However, some soils that are alternately wet and dry may occur in valleys carrying water from outside the desert (e.g., valleys of the Nile and the Indus). If required, the ustaquic soil moisture regime may be applied under such conditions.

MORPHOMETRIC CHARACTERISTICS OF WETLAND SOILS

In most descriptive soil classification systems, Fe either in its bivalent or trivalent form plays a preponderant morphometric role in the definition of soil wetness. Also, in most studies on the genesis of wetland soils, the importance of the redox reaction involving Fe is emphasized. In profile studies, dominance of gray or rusty mottled colors, or of both, is usually taken as a diagnostic characteristic of soil wetness.

For most European classification systems, the presence of rusty mottles, indicating mobility and segregation of Fe, suffices to group the pedon in a category of hydromorphic soils. The degree of wetness, according to such systems, is indicated by the grayness of the matrix colors (3).

Vizier (18) reviewed the definition and placement of hydromorphic soils in several soil classification systems. In the various Russian systems, the nature of drainage is found at a high level of the classification. In the classification based on the writings of Kovda (5), the nine major subdivisions each have a number of groups, parts of which are based on drainage. In the Russian systems, no specific placement is provided for surface-water gley conditions.

The French classifications all consider hydromorphism as a fundamental process, and hence hydromorphic soils are allotted one class at the highest level of generalization. At lower levels, the groundwater-gley soils and the surface-water or pseudogley soils are distinguished.

In the German classification system, based on the original work of Kubiena (6), drainage is used at the highest level to distinguish terrestrial, semiterrestrial, and subhydric phyla (11). At the lower levels of the German classification as it is used for soil surveys, a distinction is made between "gley-soils" and "pseudogley soils." This is also the case in the UK system, where hydromorphic soils are grouped at the highest level into three taxa -- peat soils, groundwater gley soils, and surface-water gley soils (2).

In the U.S. system, soil morphology is used in the field to infer soil wetness and moisture conditions in the pedon. In many soils, wetness can be related to the quantity, nature, and pattern of mottles, as well as to soil structure. Most soils that have repeated or ex-

tended periods of wetness are mottled or dull colored (low chroma), or both, in all or part of the profile. Mottles may indicate a zone of saturation at some period during the year. However, such mottles may also be relic features, the mottled layers or horizons being not or not regularly in a saturated and reducing state. Gray and rusty colors and color patterns in soils are at best a qualitative indication of soil wetness, past or present. They cannot be used for a quantitative determination of the wetness of any given soil without additional measurements of, e.g., the dynamics of the free groundwater or degree of reduction.

Comparing the wetness of pedons in a given landscape, it is frequently observed that the degree of dominance of low chroma grayish colors is fairly closely related to the degree of wetness and the duration of reducing conditions. In simple toposequences, the lowest members are usually the wettest with, in extreme cases, the Fe present only in the reduced form throughout the year (gley soils). In these groundwater gley soils rusty mottling is frequently along cracks and root channels while in medium to fine-textured soils the interiors of the peds retain their gray color.

Mottling in medium-textured surface-water gley soils (pseudogley), which are wetted from the surface down, is different. Here the interior of the peds retains a browner color, often with a rusty accumulation of Fe. The percolating water and some dissolved organic matter will commonly first reduce the material lining cracks and wide pores. The Fe subsequently diffuses to the interior of the peds. The O_2 still present in the ped interiors causes the formation of reddish or brownish rusty mottling.

These two "standard" types of mottling in wetland soils are fairly general; they have been observed and described in most climatic zones except in aridic soil moisture regimes. Yet again, this type of morphometric pattern is mainly of qualitative value for the soil taxonomist; it does not allow a quantitative interpretation of the present duration of wetness periods. Moreover, these morphological features cannot be correlated over wide areas to determine soil wetness; they are indicative only in the local landscape and climate context.

Another problem that confronts the taxonomist trying to characterize wetland soils is that numerous exceptions exist in the above-sketched picture of groundwater and surface-water gley mottling, so that in fact this morphology is the exception rather than the rule.

A few examples of alternative morphologies are given here:

- In wet soils belonging to sandy-skeletal or sandy families, the water movement is such that

the color pattern of gray and rusty is not indicative for a surface-water or groundwater gley. Rather, we find mostly coarse, fine mottles throughout the whole soil matrix. More sharply defined rusty mottles in sandy soils are usually confined to slight lithological discontinuities.

- If all Fe or Mn, or all of both, is removed, diagnosis of soil wetness by mottles and color patterns cannot be done. This is the case, for instance, in many wet Spodosols (Aquods) in sandy materials where free Fe and Mn are absent. Under magnification, individual sand grains are seen to be free of Fe or Mn coatings, or both. Strong brown to yellowish-brown colors in the spodic horizons of such soils are due mostly to organic matter; colors disappear when the material is heated to high temperature, and profiles can be seen to be virtually free of Fe.
- The presence of a thin Fe/Mn pan -- one of the forms of a placic horizon -- is by itself considered indicative of soil hydromorphism. These Fe/Mn pans regularly occur in Aquods, and they contribute greatly to the surficial wetness of Placaquods (2, 7).
- Some parent materials may contain no or only traces of Fe or Mn. Gray, Fe-free shales may, for instance, give soils with matrix colors typical for wet soils even though the soils are never or rarely in a wet state. A simple test with α,α'-dipyridyl will reveal that no Fe^{2+} is present in the gray parts of the solum.
- Inherited gray colors, formed due to wetness, with or without rusty mottling (relic mottles), may persist in soils long after they have been naturally or artificially drained. Again, Fe^{2+} tests will be negative during most or all of the year. Especially in older alluvial terraces which at present are well drained in view of the lowering of the erosion basis, such fossil gley phenomena may be frequently observed. In field observations, this fossil gley is difficult to distinguish from "active" gley. Gray colors and rusty mottling in such soils may therefore not be directly related to present soil wetness.
- In several wet taxa, gray and rusty mottles may be masked by the dark color of organic matter. In Andaquepts, for instance, rusty mottling is frequently missing, and though the chroma of the matrix is low, the color is more related to the specific andic properties than to reduced forms of Fe. Testing for Fe^{2+} may be indicative when soil layers are wet.

Hydromorphic Vertisols, especially low-lying pedons, are another example where the

"classical" color pattern for wet soils is not or is rarely observable.

A definition of the wetland taxa of the Vertisols (Aquerts) is now being tested by ICOMERT, but one difficulty is that no reliable and generally valid morphometric properties related to wetland conditions in Vertisols have as yet been established.

- Saturation of soils may, under certain circumstances, not lead to reduction and, hence, to relocation of Fe or Mn, or both. If water moves as a shallow interflow in an undulating to hilly relief, soils on the fringe of valleys may be water-saturated for considerable periods each year and yet not show any oxidation-reduction phenomena because of dissolved O_2, which is continuously being replenished in the moving groundwater.
- Reducing conditions, and hence redox reactions involving Fe and Mn, may not occur even in soils that are flooded for longer periods. This is frequently the situation in aridic and dry ustic moisture regimes in soils under basin irrigation such as the flooded rice lands in northwestern India (9). In these calcareous soils with low to very low organic C content (less than 0.3% C), the Eh is not sufficiently lowered for reduction reactions involving Fe oxides to take place. Free O_2 in the soil solution may be absent, thus excluding the growth of roots of common dryland crops, but no gray and mottled colors will develop, even after water saturation for several weeks, since no further lowering of the Eh takes place.

It should be clear that, although soil morphology can in many cases be used to infer soil wetness, a generally valid correlation between morphological features and degree and duration of soil wetness cannot be made. Correlation between soil color pattern and wetness of soils can only be made locally, using supporting data such as observation of soil wetness and its fluctuation, evaluation of amount, intensity and distribution of rainfall, runoff measurements, and evaporation determinations. Also of great importance is the interpretation of a wetland soil's position in the landscape.

SURFACE-WATER GLEY SOILS AND SOIL TAXONOMY

As stated in the beginning of this paper, surface-water gley soils -- commonly designated as "pseudogley soils" -- are soils whose distinct wetness of the surficial horizons is not matched by signs of wetness or pro-

longed waterlogging in the underlying horizons. Surficial wetness is caused mainly by perched water tables, whereby the "perching body" (Staukorper) may be either a lithologically different layer or a pedological horizon that becomes impermeable or poorly permeable during its formation (12).

No generally valid taxonomic definition of a surface-water gley soil is given in any of the current European systems. However, in the UK the definition of the major soil group of surface-water gley soils is based on the presence of a gleyed subsurface horizon to more than 40 cm below the mineral soil surface, the lack of gleying in underlying horizons, and the absence of permanently gleyed horizon saturated by mobile groundwater or artificially drained (2).

Essential in this definition seems to be the presence below the gleyed surface and subsurface horizon of one or more horizons, which are not saturated for longer periods and do not show gray-reduced colors. Groundwater gley, if present, starts below this intermediate nonwet horizon or horizons. Whereas this definition appears unambiguous, its use apparently is not, and available descriptions of surface-water gley soils do not always indicate a better drained, less reduced subsoil horizon.

The definition of the aquic moisture regime in Soil taxonomy (pp. 54-55) seems to preclude the soil water regime of a surface-water gley soil when it states, "For differentiation in the highest categories of soils that have an aquic regime, the whole soil must be saturated." Clearly, the definition of the aquic moisture regime as a diagnostic property, both at the suborder and at the subgroup level, was written for soils with a shallow, stable, or fluctuating groundwater table (groundwater gley soils). Dr. Guy D. Smith (pers. comm.) stated that the absence of pseudogley or surface-water gley from Soil taxonomy was caused by the lack of unambiguous taxonomic criteria to define either such a moisture regime or the taxa derived from it.

Even though the definition of the aquic moisture regime seems to exclude the notion of superficially wet soils with a drier subsoil, a perched water table causing the formation of surface-water gley soils enters the description of a score of taxa defined in the body of Soil taxonomy. In fact, most great groups of Aqualfs and Aquults have characteristics of surface-water gley soils. Most typically, Albaqualfs and Albaquults seem to be surface-water gley soils. On the contrary, virtually all wet Entisols are likely groundwater gley soils. For other orders in Soil taxonomy, surface-water and groundwater gley soils seem to be more or less indistinguishable in the taxa belonging to the aquic suborders.

Table 2 contains an abbreviated description of a pedon belonging to the Waxpool series (previously the Elbert series, Prince William County, Virginia), an example of a surface-water gley soil in the U.S.

In this case, the perching body (Staukorper) is formed by the argillic horizon, with a clay increase between the third and fourth horizon from 28 to 56%.

Further examples of US surface-water gley soils can be found in Appendix IV of Soil taxonomy. Pedon 11, described on pp. 506-507, is classified as an Aeric Glossaqualf. Matrix colors of the horizons in the upper 80 cm are low in chroma with brownish mottles. Below 80 cm, however, the chroma increases and mottling decreases.

Both this soil and the previously mentioned Waxpool series belong to an aeric subgroup, indicating that some subhorizon has a higher chroma than required for a pedon belonging to an aquic suborder.

Perusal of descriptions of profiles belonging to aeric subgroups of Aqualfs, Aquults, and, to some extent, Aquolls indicates that many such profiles have characteristics of surface-water gley soils. Yet, available data do not warrant a statement that pedons belonging to aquic suborders and aeric subgroups are synonymous with surface-water gley soils.

It should be concluded that, although the phenomenon of surface-water gley (pseudogley) is recognized in Soil taxonomy, the system does not lend itsef at present to an introduction of specific "surface-water gley taxa" unless at the series level. Establishment of objective and generally valid morphometric criteria for such taxa will be required, preferably by an international "network" of field studies.

PADDY SOILS AND SOIL TAXONOMY

"Paddy soils" connotes a class of soils occurring on land that is used for the growing of rice and of which the surface is submerged during all or part of the

Table 2. Waxpool Series, Virginia. Vegetation: forest. Soil climate: udic, thermic.

Horizon	Depth (cm)	Matrix color	Mottles	Texture
A1g	0-3	10 YR 3/2	various	Silty loam
A2g	3-23	10 YR 5/1	10 YR 6/4	Silty loam
A+Bg	23-30	10 YR 6/1	10 YR 6/4	Clayey loam
$B_{21}t$ (g)	30-58	10 YR 4/4	10 YR 5/1	Clay
$B_{22}t$ (g)	58-88	10 YR 4/4	10 YR 3/1	Clay
C_1	88-109	10 YR 4/4	10 YR 6/6	Loam
C_2	109-205	10 YR 6/6	–	Loamy sand

crop-growing season. Classification of paddy soils in the rice-growing countries of Asia has generally followed the approach of distinguishing the class at a high level of generalization from the other or "upland" soils. Various regional or national subdivisions of the class have been developed, of which the Japanese are the most complete (4). Fitting paddy soils into an overall classification system, and more specifically into Soil taxonomy, has been tried in several countries with various degrees of success, and the principles involved were reviewed by the present author (8).

In the class of "paddy soils," the change of the natural moisture regime is commonly toward a more aquatic regime, with increasing wetness of the upper part of the pedon and increasing duration of water saturation in these horizons. This change in moisture regime depends basically on two management practices:

- the leveling and bunding of individual fields, which leads to retention and ponding of water on the land, and
- irrigation of such paddy fields by water brought in from elsewhere or by overflow from a higher to a lower paddy field.

In the 1975 edition of Soil taxonomy, artificial changes in the soil moisture regimes are not recognized as diagnostic criteria unless at the lowest level of the classification. Thus, the classification of Aridisols remains unchanged when such soils are irrigated. Similarly, soils belonging to aquic taxa retain their placement in the system when artificially drained. It therefore seems that management-imposed changes in the soil moisture regime are not recognized at a high level of generalization in Soil taxonomy. It is reasoned that changes imposed by irrigation or drainage are basically short-term phenomena that disappear when the soil moisture regime reverts to its natural status.

This principle of "downgrading" the role of artificial modification of the moisture regime in the taxonomic classification may, to a large extent, be maintained when classifying soils used for growing wetland rice. It should be pointed out that in most cases changes due to the specific land use for growing wetland rice are limited to the superficial horizons so that pedons in paddy fields can generally be accommodated by the 1975 version of Soil taxonomy. This is true, for instance, for the wide alluvial and marine plains and deltas, where the use of the land for rice-growing imposes only slight changes, if any, and where the classification of soils up to the family remains unchanged under use for wet paddy land.

A minor proportion of "paddy soil" pedons have acquired characteristics that as yet have not been recognized as diagnostic in Soil taxonomy. Such changes occur when soils that have a nonaquic moisture regime

are brought under wetland rice cultivation. The surface horizons of such soils develop an "inverted gley." The morphological characteristics of an aquic soil moisture regime are imposed on the upper part of the profile, but the lower horizons remain largely unchanged, reflecting the free drainage of the original profile.

This moisture regime, for which the term "anthraquic" was proposed (9), can, when present, be recognized by introducing anthraquic subgroups of freely drained great groups on which wetland rice is grown.

Under the influence of the anthraquic moisture regime, a subsurface horizon with distinct Fe or Fe-Mn accumulation develops locally, more so in temperate climate regions than in the tropics. Profiles with such a horizon have been named Aquorizems by Kawaguchi and Kyuma (4). The exact definition and the incorporation in Soil taxonomy of these Aquorizems remain to be done. Most probably, new taxa are needed to accommodate these soils, preferably at the great group level (8).

It may be concluded that most "paddy soils" can be classified according to the present provisions of Soil taxonomy, while new taxa have to be introduced for a minority of soils in artificially ponded lands, irrespective of whether the ponding is done for rice or for another type of land use.

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PROCESSES IN WETLAND SOILS

CHEMICAL KINETICS OF WETLAND RICE SOILS RELATIVE TO SOIL FERTILITY

F. N. PONNAMPERUMA

Flooding an air-dry soil sets in motion a series of chemical and electrochemical changes that profoundly influence the soil's capacity to supply nutrients to rice. The decrease in redox potential destroys NO_3^-, decreases the availability of S and Zn, increases the availability of Fe and P, and promotes N fixation. The increase in pH of acid soils enhances the availability of P and Mo while depressing the toxicity of Mn, Al, Fe, CO_2, organic acids, and H_2S. The decrease in pH of alkaline soils increases the availability of P, Fe, and Mn. If basic cations displaced from the colloidal complex of acid soils are lost, the soils undergo further acidification on drying and reoxidation. Denitrification, ammonification, and SO_4^{2-} reduction follow first-order kinetics, and the variations of the rate constants with temperature follow the Arrhenius Law. Temperatures below 25°C retard N mineralization and favor the accumulation of organic acids, CO_2, and water-soluble Fe in acid soils. An Eh of 70-120 mV or a pE of 1.2-2.0, a pH of 6.6, and an electrical conductivity of 2 dS/m (all in the soil solution) provide a milieu favorable to rice. Under these conditions, the concentration of nutrients is adequate, and the concentrations of plant toxins are not injurious. In normal tropical soils, such conditions are attained 2-4 wk after flooding. A yield increase of about 1 t/ha can be obtained by merely keeping the soil flooded for 2 wk before planting. The dynamic nature of flooded soils is an important aspect of the fertility of wetland rice soils.

Soil fertility is the ability of a soil to deliver to roots the nutrients needed for optimum growth of a

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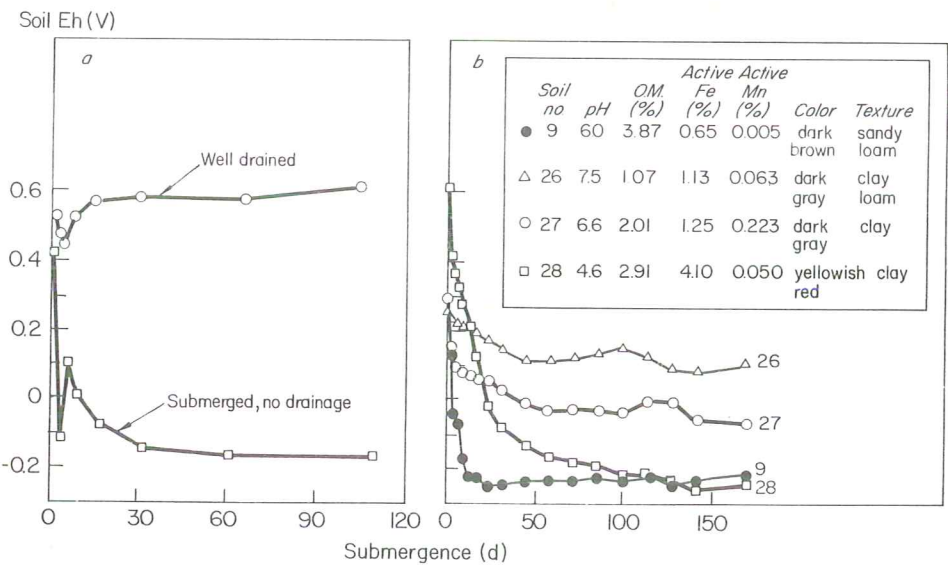
specified crop. This ability depends on the presence in the soil of an adequate supply of nutrients in forms plants can absorb, the soil's capacity to sustain the supply and to deliver nutrients by mass flow and diffusion to the root surface according to plant needs, the presence of a favorable ionic composition, and the absence of substances that poison the plant or interfere with the nutrient absorption. These factors are strongly influenced by the chemical and electrochemical changes brought about by flooding.

The main electrochemical and chemical changes that affect fertility include decrease in redox potential (Eh); changes in both soil and floodwater pH; changes in electrical conductivity (EC); denitrification; accumulation of NH_4^+; N fixation; reduction of Mn(IV), Fe(III), and SO_4^{2-}; changes in the availability of N, P, K, S, B, Cu, Fe, Mn, Mo, and Zn; and production of CO_2, organic acids, and H_2S. The rates of these changes (chemical kinetics) can be described mathematically or graphically (16).

ELECTROCHEMICAL KINETICS

Redox potential

Kinetics. The Eh or pE (equal to Eh/0.059) falls sharply upon flooding, reaches a minimum within a few days, rises rapidly to a maximum, and then decreases asymptotically with time (Fig. 1a). Soil properties markedly influence Eh kinetics (Fig. 1b). The presence



1. a) Eh kinetics in a well-drained and a submerged soil. b) Influence of soil properties on Eh kinetics in four submerged soils.

of organic matter, a low content of NO_3^- and MnO_2, and a temperature of 30-35°C favor Eh decrease, and a value as low as -0.25 V may be attained within 2 wk of flooding.

Fertility effects. The Eh or pE determines the stable form of N in a soil and therefore its availability to rice. The equation for the NO_3^--N_2 system

$$pE = 21.06 - 1/5\ pNO_3^- + 1/10\ pN_2 - 6/5\ pH$$

shows that at the pE values of submerged soils (pE = -1 to 3) NO_3^- is highly unstable. The instability of NO_3^- in reduced soils means that within a few days of submergence the bulk of the original or added NO_3^- is lost by denitrification. Since rice can utilize NO_3^-, denitrification represents the loss of a valuable nutrient. But low Eh favors N fixation (19).

A low Eh increases the availability of P, Fe, Mn, and Mo, but decreases that of S and Zn (21, 22). At a pE of -1.0 and a pH of 7.0, the concentration of water-soluble Fe^{2+} is high enough to poison the rice plant directly and to interfere with uptake of P and K, but at a pE of 2.0 and a pH of 7.0, rice may suffer from Fe deficiency. The increase in concentration of Fe and Mn may benefit rice on alkaline soils, whereas the decrease in concentration of SO_4^{2-} may cause S deficiency in soils low in S (11). The increase in availability of P and Fe following soil reduction benefits rice (17, 18).

The optimum Eh for wetland rice is 70-120 mV (pE of 1.2-2.0) at pH 7.0 in the soil solution (21, 22).

Soil pH

Kinetics. When an aerobic soil is submerged, its pH decreases during the first few days, reaches a minimum, and then increases asymptotically to a fairly stable value a few weeks later of 6.7-7.2 in a 1:1 soil water suspension or 6.5-7.0 in the soil solution (18, 19). The overall effect of flooding is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils. Thus submergence makes the pH of all soils -- except acid peats and those low in active Fe -- converge to 7 (Fig. 2). Low temperature retards pH changes (3).

The increase in pH of most acid mineral soils is due to the reduction of Fe(III) to Fe(II) and can be described by

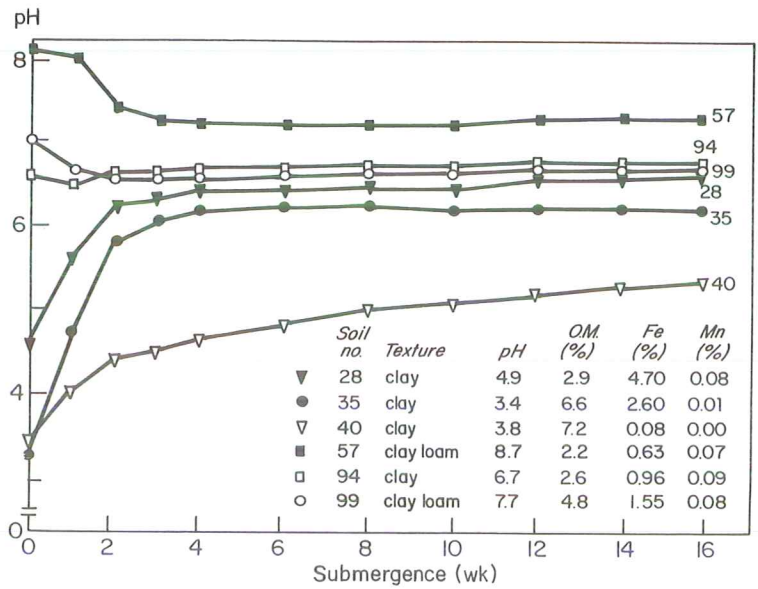
$$Eh = 1.06 - 0.059 \log Fe^{2+} - 0.177\ pH$$

$$\text{or } pE = 17.87 + pFe^{2+} - 3\ pH$$

The decrease in pH of alkaline soils is due to CO_2 accumulation and is given by

$$pH = 6.0 - 2/3 \log P_{CO_2} \qquad \text{Calcareous soils}$$

$$pH = 7.85 + \log (\text{alkalinity}) - \log P_{CO_2} \qquad \text{Sodic soils}$$



2. Kinetics of the pH values of some submerged soils.

Fertility effects. The pH of a submerged soil markedly influences the concentration of nutrients and toxic substances through its effects on chemical equilibria, sorption and desorption, NH_3 volatilization, and microbial processes that release or destroy plant nutrients or that generate toxic substances.

The activities (the concentrations will be higher) of water-soluble Fe and Al at different pH are given below (21).

pH	Al (μmol/litre)	pH	Fe (μmol/litre)
3.5	2600	6.5	6200
4.0	260	7.0	620
4.5	26	7.5	6.2
5.0	2.6	8.5	0.62

These figures show toxic concentrations of Al below pH 4.5. Such pH values are encountered in dry or recently flooded acid sulfate soils and strongly acid upland soils. A benefit of flooding rice soils is that flooding virtually eliminates Al toxicity, but Fe toxicity is likely to occur in most mineral soils that do not attain a pH exceeding 6.5 after flooding. Iron deficiency is possible on flooded high-pH soils that are low in organic matter.

The toxicity of CO_2, organic acids, and H_2S is more severe at low pH than at high pH because the concentration of the toxic species (H_2CO_3, RCOOH, and H_2S) increases as the pH decreases.

The increase in pH of acid soils and the decrease in pH of calcareous and sodic soils enhance the availability of P. At high pH and low P_{CO_2} (5 kPa or

0.05 bar), the concentration of Ca and Mn may be too low for rice growth, as shown in the following (21):

pH	Ca (μmol/litre)	Mn (μmol/litre)
8.5	1.4	0.026
8.0	14	0.26
7.5	140	2.6
7.0	1400	26

The decrease in pH of sodic soils on flooding alleviates Ca and Mn deficiencies. Incorporation of organic matter enhances the flooding effect through CO_2 and acid production. The increase in pH of acid soils increases the availability of P and Mo.

A pH of about 7 favors microbial activity because the main microorganisms in reduced soils are anaerobic bacteria, which function best at a pH of about 7. Thus ammonification, denitrification, SO_4^{2-} reduction, and CH_4 formation are favored by the pH changes in submerged soils.

The optimum pH (measured in the solution of the submerged soil) for rice is about 6.6. At that pH, microbial release of N and P is fast; the supplies of Cu, Fe, Mn, Mo, and Zn are adequate; and the concentrations of substances that interfere with nutrient uptake -- such as Al, Fe, Mn, CO_2, and organic acids -- and H_2S are below toxic levels. In the tropics, mineral soils with an organic matter content >2% attain this pH 2-4 wk after flooding. Delaying transplanting until 2 wk after submergence increased yield by 1 t/ha in the dry season and by 0.8 t/ha in the wet season over planting at submergence (6).

Floodwater pH

Kinetics. The pH of the standing water in a rice field is determined by the alkalinity of the irrigation water, the soil pH, algal activity, the plant canopy, and fertilization. In the presence of algae the pH undergoes marked diurnal fluctuations, with daytime values as high as 10.5 and nighttime values down to 8.5 (14). The daytime increase in pH is due to CO_2 removal by algal photosynthesis.

Fertility effects. The rise in pH increases the concentration of NH_3 at a given total NH_4^+ concentration, which in turn enhances NH_3 loss from the floodwater. The loss in 5 d was 49% in a sodic soil (pH 8.6) and only 6% in soil with a pH of 5.7 (10). The pH increase may also cause Fe and P deficiency in algae and azolla.

Electrical conductivity

Kinetics. The EC of the solution of most soils increases on flooding, attains a maximum, and declines to a fairly stable value that varies with the soil. The increase is due to mobilization of Fe^{2+} and Mn^{2+};

formation of NH_4^+, HCO_3^-, and $RCOO^-$; and displacement of cations from soil colloids by Fe^{2+}, Mn^{2+}, and NH_4^+. The subsequent decrease is caused by precipitation of Fe^{2+} as $Fe_3(OH)_8$ and FeS, precipitation of Mn as $MnCO_3$, loss of CO_2, and conversion of $RCOO^-$ to CH_4. Thus there is a close correlation between the kinetics of these ions and the changes in EC (21).

Fertility effects. In a normal submerged soil the peak EC is around 2-4 dS/m, but sandy soils rich in organic matter and some acid sulfate soils may attain values exceeding 4 dS/m, the harmful limit for rice. An EC of 2 dS/m favors rice growth. Cations displaced by Fe^{2+}, Mn^{2+}, and NH_4^+ while the soil is in the reduced state may be lost in percolating waters. On drying, oxidation of Fe^{2+} and NH_4^+ acidifies the soil.

As the EC increases, so does ionic strength (I). The relationship between EC and I is given by I = 14-16 EC (29). The increase in ionic strength depresses activity coefficients and alters the concentrations of ecologically important ions.

KINETICS OF NUTRIENTS

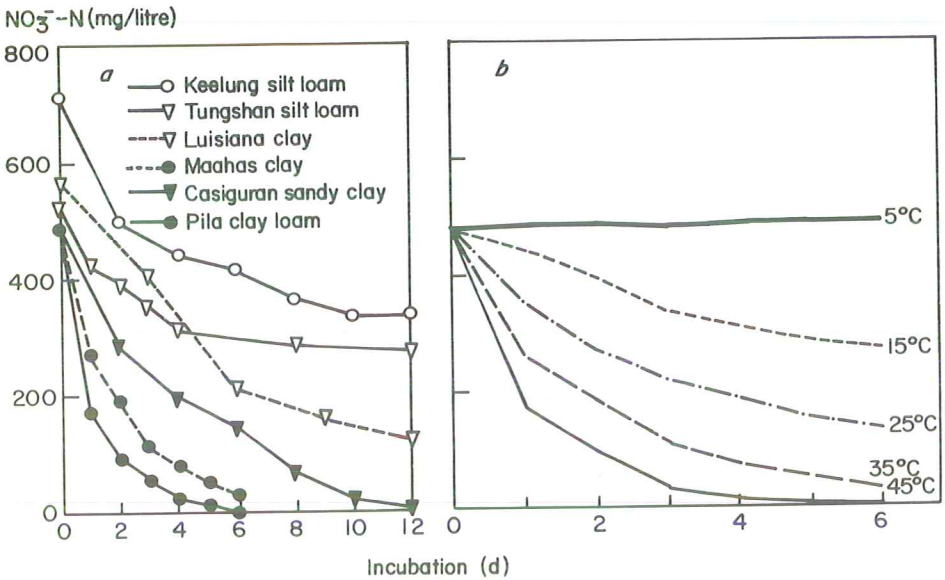
The dynamic nature of flooded soils causes marked changes in fertility during a season through processes that release or inactivate nutrients. The elements affected most are N, P, S, Cu, Fe, Mn, Mo, and Zn.

Nitrate

Kinetics. Nitrate is present in aerobic soils at the time of flooding. It is also present in the floodwater, in the surface soil, and in the oxidized rhizosphere. Nitrate is rapidly reduced to N_2O and N_2 in the anaerobic bulk of flooded soils. The rate of disappearance of NO_3^- varied markedly with soil and temperature (Fig. 3). Denitrification (as measured by NO_3^- disappearance) was fastest in Pila clay loam (pH 7.1, OC 2.1%), moderately fast in Luisiana clay (pH 4.7, OC 2.1%), and slowest in Keelung silt loam (pH 7.7, OC 3.9%) despite its high pH and high organic C content. In all soils denitrification was hardly detectable at 5°C and increased rapidly with increase in temperature.

Disappearance of NO_3^- follows first-order kinetics ($-\frac{dc}{dt} = kc$), with rate constants that vary with the soil (8). Gupta (5) showed that the variation of the rate constant with temperature followed the Arrhenius Law, $k = A \exp(-Ea/RT)$, and that the mean Q_{10} for 6 soils in the range 15-35°C was 2.1-2.5 (5).

Fertility effects. In tropical rice soils, NO_3^- disappears within a few days of flooding,



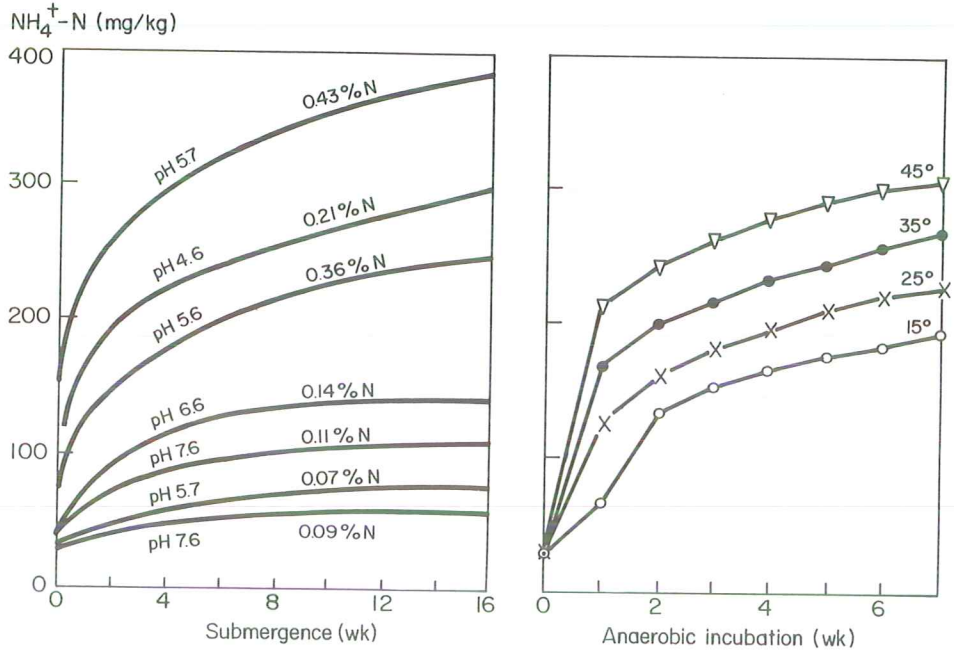
3. a) Kinetics of denitrification in six submerged soils at 35°C. b) Kinetics of denitrification in submerged Maahas clay at five temperatures.

largely because of denitrification. A survey of 28 Philippine wetland rice soils sampled just before flooding for the rice crop revealed the presence of 5-39 mg NO_3^--N/kg soil with a mean of 13 mg/kg. If all the NO_3^- is denitrified, the Philippines suffers an annual loss of about 78,000 t N from its 3.0 million ha of wetland rice fields. The N loss can be minimized by keeping the soils continuously flooded. Alternate wetting and drying of a soil carrying a vigorously growing rice crop does not cause appreciable denitrification (12).

Ammonium

Kinetics. The mineralization of organic N in submerged soils stops at the NH_4^+ stage. The velocity of NH_4^+ release is therefore a good index of the capacity of a soil to meet the N demands of a rice crop.

The kinetics of ammonification varies with the soil, temperature, and pretreatment of the soil. Figure 4 shows that soils high in N produced more NH_4^+ faster than the others, and that half the N mineralized in 16 wk was released in the first 2 wk. Ammonification followed first-order kinetics, the mean Q_{10} for 6 soils in the range 15-35°C was 1.5-1.7, and the variation of the rate constant with temperature followed the Arrhenius Law (5). Air-drying 4 peat soils before anaerobic incubation caused a release in 8 wk of 200-500 mg NH_4^+/kg compared with almost zero for the nondried wet peat soils (24).



4. Influence of soil properties (a) and temperature (b) on NH_4^+ release in submerged soils.

A considerable proportion of the NH_4^+ mineralized in a submerged soil may be in the solution phase, especially in sandy soils. This form of NH_4^+ is highly mobile and is liable to loss by leaching. A sandy soil well supplied with organic matter built up an NH_4^+ concentration of nearly 70 mg/litre in 75 d while a neutral soil low in organic matter accumulated barely 5 mg/litre in the same period (18). Temperature markedly influences the NH_4^+ concentration in the soil solution. The concentration of NH_4^+ 2 wk after submergence of a silt loam (pH 7.9, OC 4.0%, CEC 17.5 meq/100 g) was 170 mg/litre at 30°C compared with 90 mg/litre at 20°C (3).

Fertility effects. The kinetics of NH_4^+ is important in rice nutrition because N holds the key to the productivity of rice, up to 70% of the N taken up by a rice crop even in fertilized fields comes from the soil, and grain yield is highly sensitive to an excess or deficiency of N at critical growth phases. The implications for rice fertilization are that soils low in total N (<0.1%) need basal and top dressings, soils moderate in N (0.1-0.2%) need only a top dressing, and mineral soils high in N (>0.2%) may need no fertilizer N for a yield of 5 t/ha. Cold soils and continuously wet soils need basal N fertilization regardless of soil N content. Ammonium toxicity may occur on sandy soils high in organic matter in equatorial lowlands.

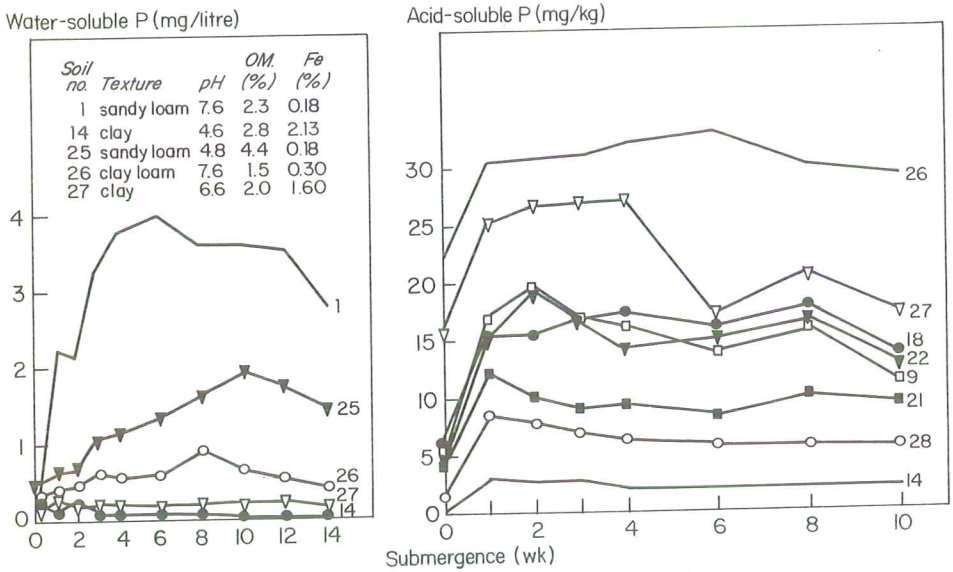
Phosphorus

Kinetics. When a soil is flooded, the concentrations of water- and acid-soluble P increase, peak, or plateau, and then decrease (Fig. 5). The peak water-soluble values were lowest for the acid clays high in active Fe and highest for a sandy soil low in Fe. The concentration of P soluble in an acetate buffer at pH 2.7 includes the phosphates of Fe^{2+}, Mn^{2+}, and Ca^{2+}. The increase in acid-soluble P was highest in the clay loam (soil 26: pH 7.6, OC 0.9%, active Fe 0.3%), intermediate in the sandy loams high in organic C and low in active Fe (soils 9, 18, 22), and least in the acid clays high in active Fe (soils 14, 21, 28).

The increase in solubility of P caused by flooding is caused by

- reduction of $FePO_4 \cdot 2H_2O$ to $Fe(PO_4)_2 \cdot 8H_2O$,
- desorption following reduction of Fe (III) hydrous oxides to Fe (II),
- hydrolysis of $FePO_4$ and $AlPO_4$ in acid soils,
- release of occluded P, and
- anion exchange.

The subsequent decrease may be due to resorption on clays and Al hydroxides, precipitation, or microbial destruction of organic anions that earlier exchanged for phosphate ions. The increase in concentration of water-soluble P on flooding calcareous soils may be due to the increase in solubility of octacalcium phosphate [$Ca_4(PO_4)_3 \cdot 2.5H_2O$], β-tricalcium phosphate [$\beta Ca_3(PO_4)_2$], hydroxy apatite [$Ca_5(PO_4)_3OH$], and fluorapatite [$Ca_5(PO_4)_3F$] accompanying pH decrease. Their solubility is higher at pH 6.5 than at pH values above 7.0 (13).



5. Kinetics of water-soluble and acid-soluble phosphorus in submerged soils.

Fertility effects. Although the increase in availability of P is regarded as a benefit of flooding rice soils (4, 15, 18), the effect on rice growth may not be appreciable in acid clays high in active Fe.

The kinetics of acid- and water-soluble P may suggest that a P test on an aerobic soil may not provide a satisfactory index of P availability after flooding. To test this, available P (Olsen) in 17 Philippine wetland rice soils was determined at 0, 15, and 30 days after flooding and correlated with grain yield and P uptake. The soil test values at each sampling date correlated highly with grain yield and P uptake (9). Thus the test on the air-dry soil by Olsen's method is a satisfactory measure of P availability, which Chang confirmed (2).

Sulfate

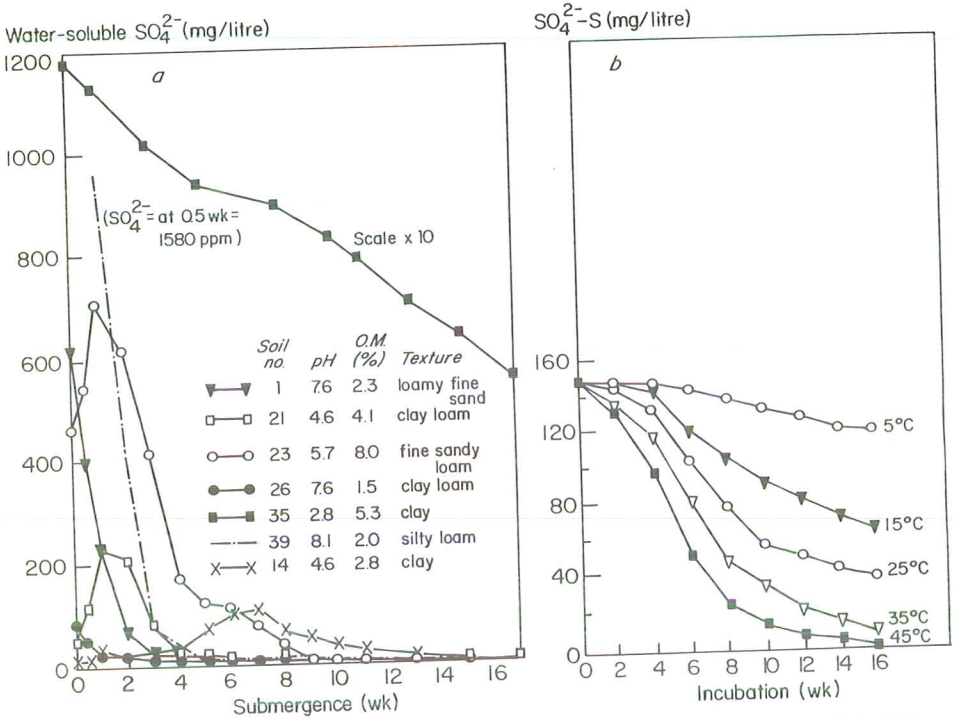
Kinetics. The kinetics of water-soluble SO_4^{2-} (which is a measure of SO_4^{2-} reduction) in anaerobic soils depends on soil properties and temperature. In neutral and alkaline soils, the SO_4^{2-} concentration decreased rapidly and was reduced to zero within 6 wk of flooding. In acid soils it first increased because of desorption and then decreased to zero. In the acid sulfate soil (soil 35), the SO_4^{2-} concentration decreased steadily but stood at 500 mg/litre even 16 wk after submergence (Fig. 6).

Sulfate reduction followed first-order kinetics with velocity constants that were high in alkaline soils and low in acid soils (8). The rate of SO_4^{2-} reduction increased rapidly with temperature, and the variation of the rate constants with temperature followed the Arrhenius Law (5).

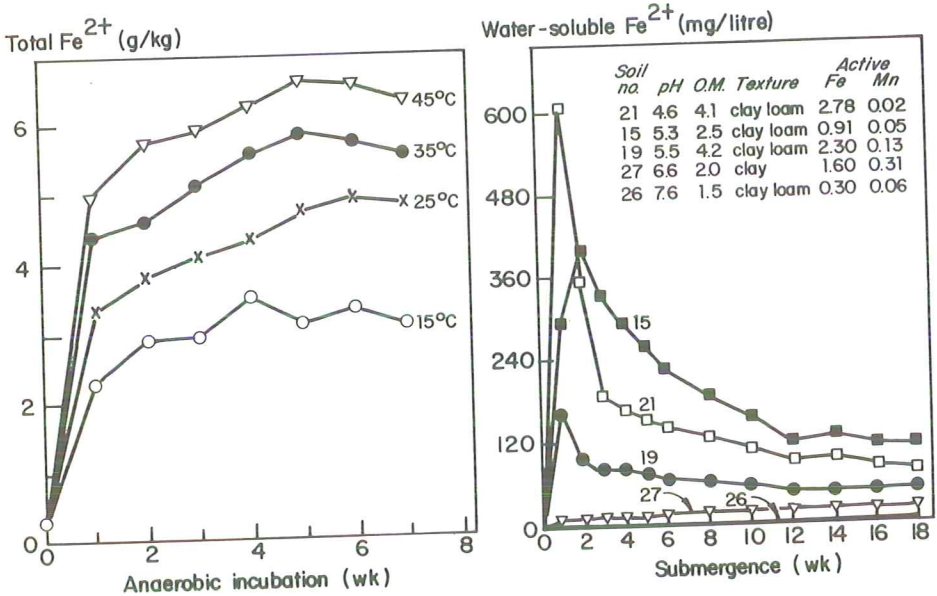
Fertility effects. Sulfate reduction may cause S deficiency in soils low in available S, Zn deficiency due to precipitation of ZnS, and H_2S toxicity in soils low in Fe and in acid sulfate soils.

Iron

Kinetics. The most conspicuous change caused by flooding dry soil is the reduction of Fe(III) to Fe(II) and the accompanying increase in the solubility of Fe. The reduction follows a roughly asymptotic course (Fig. 7), but the velocity of reduction and the maximum amount reduced vary with the active Fe and organic matter contents and temperature (5). The relationship between the active Fe content and the rate of Fe(III) reduction was linear ($r = 0.96^{**}$), regardless of organic matter content and pH (7). The rate of Fe(III) reduction and the maximum amount reduced increased with temperature in the range 15-45°C (Fig. 7).



6. Influence of soil properties (a) and temperature (b) on kinetics of sulfate reduction in submerged soils.



7. Influence of temperature on total Fe^2 and water-soluble Fe^{2+}.

The distribution of reduced Fe between the solid and solution phases is controlled by pH, organic matter content, CEC of the soil, and precipitation reactions. During soil submergence the concentration of water-soluble Fe^{2+} increases to a peak value and then declines or reaches a plateau (Fig. 7). Those changes vary with the pH and organic matter content of the soil, the content and reactivity of the Fe(III) oxides, and the salt content of the soil. The average concentrations of water-soluble Fe^{2+} are highest (>3000 mg/litre) in acid sulfate soils with a high content of reactive Fe(III) hydrous oxides and lowest (<1 mg/litre) in alkaline soils low in organic matter. Low temperature (3) or the presence of NO_3^- (29) retards the release of water-soluble Fe^{2+} but does not prevent the later buildup of high concentrations. High concentrations of Fe^{2+} may persist in cold acid soils. The concentration of water-soluble Fe^{2+} at any instant can be described for most soils by the equilibrium:

$$Fe(OH)_3 + 3\ H^+ + e = Fe^{2+} + 3\ H_2O$$
$$\text{with } Eh = 1.058 - 0.059 \log Fe^{2+} - 0.177\ pH$$
$$\text{or } pE = 17.87 + pFe^{2+} - 3\ pH$$

Exceptions are organic soils, acid sulfate soils, soils low in active Fe, and soils with highly crystalline Fe(III) oxides. For such soils the concentrations of Fe^{2+} are lower than those predicted by the above equations. After the peak, the water-soluble Fe^{2+} concentration (with the exceptions given earlier) is governed by the equilibrium

$$Fe_3(OH)_8 + 8\ H^+ + e = 3\ Fe^{2+} + 8\ H_2O$$
$$\text{with } Eh = 1.374 - 0.0885 \log Fe^{2+} - 0.236\ pH$$
$$\text{or } pE = 23.27 + 3/2\ pFe^{2+} - 4\ pH$$

For Tropaquults, the pH-Fe relationship is

$$pH + 1/2 \log Fe^{2+} = 5.4$$

For other soils the constant may be as low as 4.8.

Fertility effects. The kinetics of water-soluble Fe^{2+} markedly influences the chemical and electrochemical changes in paddy soils, the loss of cations from the soil, and the nutrition of the rice plant.

The increase in solubility of Fe is an important benefit of flooding rice soils because O_2 secretion by rice roots increases the rice plant's apparent Fe requirement (20) but an excess harms rice directly (25) and indirectly by impeding N and K uptake (28). Toxic Fe^{2+} concentrations occur in strongly acid soils. Iron toxicity is corrected by adding lime or MnO_2 or by prolonged submergence. Iron deficiency may occur even in flooded soils if the pH and pE are high, as in alkaline soils low in organic matter; it is corrected by applying organic matter, Fe salts, or H_2SO_4 (23).

Manganese

Kinetics. On flooding a soil, Mn(IV) and Mn(III) hydrous oxides are reduced to Mn^{2+}. The reduction occurs at a higher Eh than Fe(III) oxides and therefore precedes that of Fe(III). Gupta found that the reduction followed an asymptotic course and in most soils was complete within 2 wk of submergence (5). Besides, the rates of reduction in all but 1 of the 11 soils he studied were virtually independent of temperature in the range 15-45°C. The concentration of total Mn^{2+} in wetland rice soils ranges from 0.005 to 0.3%.

After reduction, the concentration of water-soluble Mn^{2+} increases, peaks as high as 90 mg/litre, and declines or plateaus at 10-20 mg/litre. The peaks are sharp and appear early in acid soils high in Mn and organic matter. The decline in concentration after the peak is due to the precipitation of $MnCO_3$. The fairly stable concentrations attained after several weeks of submergence are described by the equation

$$pH + 1/2 \log Mn^{2+} + 1/2 \log P_{CO_2} = 4.1$$

Fertility effects. Water-soluble Mn^{2+} moves down the profile of wetland rice soils. The eluviation of Mn^{2+} may cause Mn deficiency in sandy soils (15). Although flooding increases the solubility of Mn^{2+}, Mn deficiency in wetland rice may occur in sodic and calcareous soils low in organic matter and in sandy soils. Manganese toxicity has not been observed in wetland rice, though acid upland soils may have the problem (20).

Copper, molybdenum, and zinc

Kinetics. Flooding a soil causes a decrease in the concentrations of water-soluble Cu and of Zn, but an increase in the concentration of Mo (Table 1). The concentration of B is not appreciably affected. The decrease in solubility of Cu and Zn may be due to their

Table 1. Kinetics of water-soluble B, Cu, Mo, and Zn in two submerged soils.

Element	Concentration (mg/litre)			
	1 wk	2 wk	4 wk	6 wk
	Luisiana clay (pH 4.8, O.M. 2.8%)			
B	0.55	0.49	0.46	0.30
Cu	0.11	0.11	0.04	0.02
Mo	0.18	0.06	0.15	0.24
Zn	0.30	0.09	0.08	0.03
	Maahas clay (pH 6.6, O.M. 2.0%)			
B	1.80	1.01	1.15	1.18
Cu	0.06	0.05	0.03	0.02
Mo	0.04	0.09	0.17	0.12
Zn	0.18	0.08	0.06	0.03

removal as insoluble sulfides (1). The increase in solubility of Mo is due to desorption.

Fertility effects. Zinc deficiency occurs on continuously flooded soils. A simple remedy is to drain the soil and aerate it temporarily.

KINETICS OF TOXINS

The anaerobic decomposition of organic matter produces an array of substances whose kinetics varies with the soil, nature and amount of added organic matter, and temperature (26). Some of these substances poison rice roots or they interfere with water and nutrient uptake. Excessive CO_2, organic acids, and H_2S harm rice plants, so their kinetics are nutritionally important.

Carbon dioxide

Kinetics. One to three tons of CO_2 are produced in the plowed layer of 1 ha of a flooded soil during the first few weeks of submergence. The partial pressure of CO_2 (P_{CO_2}) in conjunction with pH is a good measure of CO_2 production (19).

The P_{CO_2} in a soil increases after submergence, reaches a peak of 20-80 kPa 1-3 wk later, and declines to a fairly stable value of 5-20 kPa. Acid soils high in organic matter and low in active Fe give higher P_{CO_2} values throughout the season than neutral soils. Temperature markedly affects P_{CO_2} kinetics, especially in acid soils.

Using ^{14}C-labeled rice straw, H. U. Neue (unpubl.) showed that CO_2 production in a submerged soil leveled off after 35 d while CH_4 formation continued for 80 d. The half-life of the incorporated straw was 43 d.

Fertility effects. Carbon dioxide injury may occur in acid rice soils high in organic matter and low in active Fe, especially at low temperatures (3). Carbon dioxide depresses the pH of alkaline soils and makes P, Fe, and Zn more available.

Organic acids

Kinetics. The main organic acids found in anaerobic soils are the volatile aliphatic acids: formic, acetic, and propionic acids. Acetic acid is by far the most abundant (8, 26, 27). When a soil is submerged, the concentrations of these acids increase to peak values of 10-40 mM/litre (depending on the soil, kind and content of organic matter, and temperature) and decline to less than 1 mM/litre a few weeks later. Sandy soils high in organic matter build up high concentrations, especially at temperatures below 20°C. In nearly neutral soils the concentration does not exceed 10

mM/litre at any stage of submergence. The decrease in concentration of the acids with time is due to their decomposition with CH_4 formation. Application of straw or green manure increases the concentration of organic acids (26).

Fertility effects. Organic acid injury to rice may occur on cold acid soils and soils heavily manured with organic materials. In tropical lowlands the adverse effects disappear 2-4 wk after flooding.

Hydrogen sulfide

Kinetics. The concentration of water-soluble H_2S increases on submergence, reaches a peak value 2-3 wk after submergence (at a temperature of about 30°C), and then declines to a fairly stable value. The peak and final concentrations are determined by the active Fe and SO_4^{2-} content of the soil (Table 2). The increase in concentration of H_2S is due to SO_4^{2-} reduction, and the decline after the peak value is caused by its removal as insoluble FeS. In normal soils this reaction lowers the H_2S concentration to less than 10^{-8} mol/litre, but soils high in SO_4^{2-} and low in active Fe can build up high H_2S concentrations.

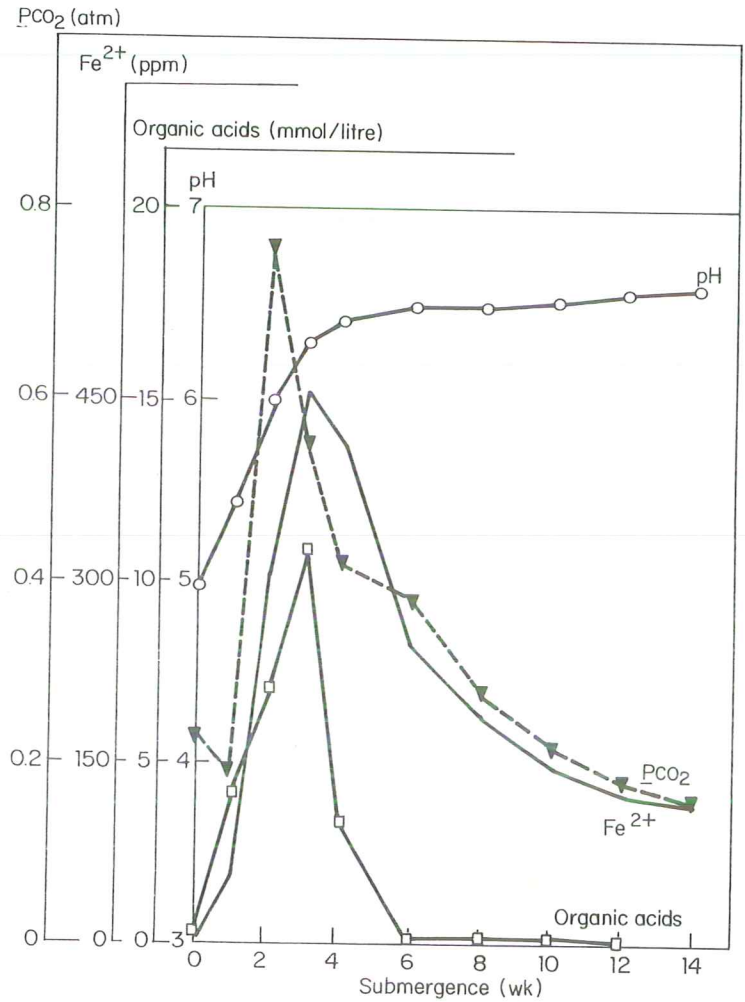
Fertility effects. Hydrogen sulfide at concentrations as low as 0.1 mg/litre inhibits respiration and retards water and nutrient uptake. The differential retardation of nutrient uptake causes nutrient imbalance and susceptibility to diseases (18). Hydrogen sulfide toxicity is one cause of the poor rice growth on acid sulfate soils and coastal peats.

FLOODING AND FERTILITY

Flooding a soil sets in motion chemical and electrochemical processes that affect the supply of nutrients and their uptake by rice. After a 2- to 4-wk period of rapid changes, the processes tend to stabilize (Fig. 8). The stable milieu favors rice because the nutrient supply is adequate and the level of toxins is low. A

Table 2. Influence of soil properties on hydrogen sulfide kinetics in four submerged soils.

pH	O. C. (%)	Active Fe (%)	SO_4^{2-}-S (mg/kg)	Water-soluble H_2S (μg/litre)				
				1 wk	2 wk	4 wk	6 wk	10 wk
6.8	1.1	1.6	95	1	1	4	1	1
4.7	1.8	2.9	47	11	9	26	3	1
4.8	1.6	0.50	56	139	542	327	42	20
3.8	3.6	0.85	563	242	13 300	10 090	1 430	100

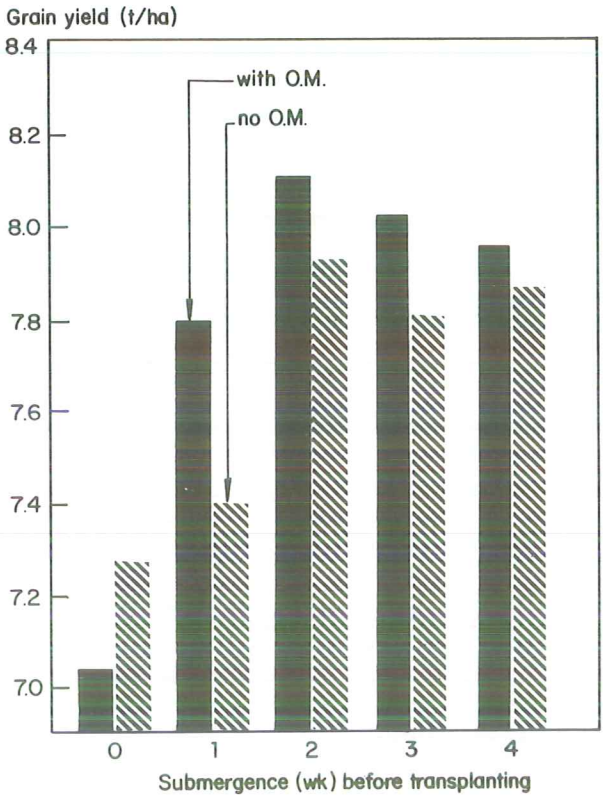


8. Kinetics of pH, PCO_2, water-soluble Fe^{2+}, and organic acids in flooded Luisiana soil at 30°C.

yield increase of about 1 t/ha can be obtained by merely delaying transplanting for 2 wk after flooding (Fig. 9).

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SOIL WETNESS AND AERATION IN SELECTED SOILS WITH AQUIC MOISTURE REGIMES IN THE MISSISSIPPI AND PEARL RIVER DELTAS[1]

W. B. PARKER, S. P. FAULKNER, and W. H. PATRICK, JR.[2]

The important functions of wetlands in the United States have become apparent in recent times, bringing to light the need for protecting this resource through a national regulatory program including the passage of a Presidential Executive Order and considerable research. The purpose of this research has been to study soil saturation, moisture content, redox potential, soil wetness characteristics, and vegetation, and to relate these to wetlands.

This research is expected to confirm some of the assumptions pertaining to certain chemical and physical changes that occur in wet soils as they go through seasonal cycles and the effects on vegetation during these changes. Five transects, one in Mississippi and four in Louisiana, were established along a gradient from wetland to nonwetland. A total of 24 plots were established on these transects, with each plot containing two stations with the following equipment: four oxidation-reduction electrodes, four oxygen-diffusion chambers, three thermisters, all placed at different depths, one water table well, and one moisture gauge access tube. The study confirmed and quantified for five soil series that oxygen content and redox potential decrease with soil moisture and depth. Also, it was observed that mean soil temperatures were warmer on the wetter plots and during the dry cycle and the growing season.

The increasing national and international attention drawn to wetlands has intensified the need for reliable

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information on the status and extent of wetland resources. In the United States, federal legislation and executive orders to protect the nation's wetlands have required federal agencies to develop methods for defining, classifying, and delineating wetlands. The three federal agencies with major responsibilities for administering these regulations are the U.S. Environmental Protection Agency, the U.S. Army Corps of Engineers, and the U.S. Fish and Wildlife Service. With assistance from other agencies such as the U.S. Soil Conservation Service, they have been developing and refining parameters to identify, classify, and delineate wetlands. These parameters are vegetation, soils, and hydrology.

DEFINITION OF WETLANDS

The two major definitions of "wetland" that affect this paper are those of the Army Corps of Engineers, which is directly involved in regulating wetlands, and the Fish and Wildlife Service, which is responsible for protecting important habitats such as wetlands.

Army Corps of Engineers definition

The Army Corps of Engineers defines wetlands as those areas that are inundated or saturated by surface water or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas (7).

Fish and Wildlife Service definition

Wetlands are defined in the "Classification of Wetlands and Deepwater Habitats of the United States" by Cowardin et al (6) as lands where saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the soil and on its surface. The single feature that most wetlands share is soil or substrate that is at least periodically saturated with or covered by water. The water creates severe physiological problems for all plants and animals except those adapted for life in water or in saturated soil. Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water. For the purposes of this classification, wetlands must have one or more of the following attributes:

- At least periodically the land supports predominantly hydrophytes,

- The substrate is predominantly undrained hydric soil, and
- The substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

A list of wetland plants (hydrophytes) and a list of wetland soils (hydric) are an integral part of the wetlands definition. The list of plants and soils will support interpretations and uses of the definition of wetlands and aid in identifying and delineating wetlands. The Fish and Wildlife Service is developing the list of hydrophytes and the Soil Conservation Service the list of hydric soils.

STRATEGY FOR DEVELOPING A LIST OF HYDRIC SOILS

The strategy for developing the list of hydric soils was first to refine the concept, then to summarize it as a definition, to field-test the definition, and finally to identify those soil characteristics that are indicative of hydric conditions.

In the beginning all soils with aquic and peraquic moisture regimes were considered hydric. During the field studies, soils with aeric subgroups in aquic suborders having thermic and hyperthermic temperature regimes were considered too dry to be included as hydric. Because these soils are dry during the early part of the growing season, neither the plant community nor the soils reflect a wetland condition. Also, some soils with alfic, arenic, entic, grossarenic, and ultic subgroups of aquic suborders are not wet enough to be considered hydric. An interagency study team (consisting of the Soil Conservation Service, Fish and Wildlife Service, Army Corps of Engineers and, when possible, the Environmental Protection Agency and other federal and state agencies) designated key states in which to do field studies on the correlation of plant communities and wet soils. These field studies stressed the need for more definite research on soil saturation and plant adaptation to certain kinds of wet soils.

During these field studies in the Eastern Gulf and Atlantic coastal flatwoods major land resource areas (13), Aquults and Aqualfs with light-colored surface layers seemed to have more yellow and red mottles and were not usually considered hydric by the study group. The Aquults and Aqualfs with dark-colored surface layers were more gray in the subsoil and were usually considered hydric by the group. The Ochracuults and Albaqualfs that were highly mottled, particularly with red mottles, seemed to support a more mesophytic-type of plant community and were not considered hydric.

The water regime of wetlands can usually be correlated with the soil moisture regimes of Soil taxonomy

(14). There are five such soil moisture regime classes, viz., aquic, aridic, torric, udic, and ustic. The aquic implies a reducing regime that is virtually free of dissolved O_2 because the soil is saturated by groundwater or by water of the capillary fringe. The aquic moisture regime in the highest categories of soils seems to correlate best with the hydric soils.

The soils most likely to fit the definition of hydric soils are those in Typic subgroups of aquic suborders and other subgroups of aquic suborders with an equivalent degree of wetness.

DEFINITION OF HYDRIC SOILS

The intent of the definition of hydric soils is to identify soils that favor the production and regeneration of hydrophytic vegetation. Hydric soils are saturated or flooded long enough to produce anaerobic conditions that affect the plant growth. There is a high degree of correlation between present hydrophytic plant communities and hydric soils. The presence of free water in or on the soil for extended periods and a virtual absence of O_2 are key attributes of hydric soils. In identifying hydric soils, hydrology, land management, and observable soil properties as well as elements of the definition are evaluated. Soils that were wet at one time but that have been drained or protected through natural or artificial means are not considered hydric soils. Neither are soils that are not naturally wet but are periodically flooded or saturated for specific management purposes. For example, some soils with the morphological properties of wet soils are no longer wet because the natural groundwater level has dropped since they formed; other soils such as those covered by recent impoundments like beaver ponds do not have the morphology of wet soils but are considered hydric soils. Phases of soil series were identified by cooperators in the National Cooperative Soil Survey (NCSS) as those soils that consistently meet the definition of hydric soils. "Soil" in this context refers to a technical grouping that consists of phases of a soil series and not to the names of map units on a soil survey map; consequently, the operational use of soil maps to assist in designating areas of hydric soils may need additional guidelines.

Hydric soils thus have one or both of the following properties:

- The soil is saturated at or near the soil surface with water that is virtually lacking in free O_2 for significant periods during the growing season, or
- The soil is flooded frequently for long periods during the growing season.

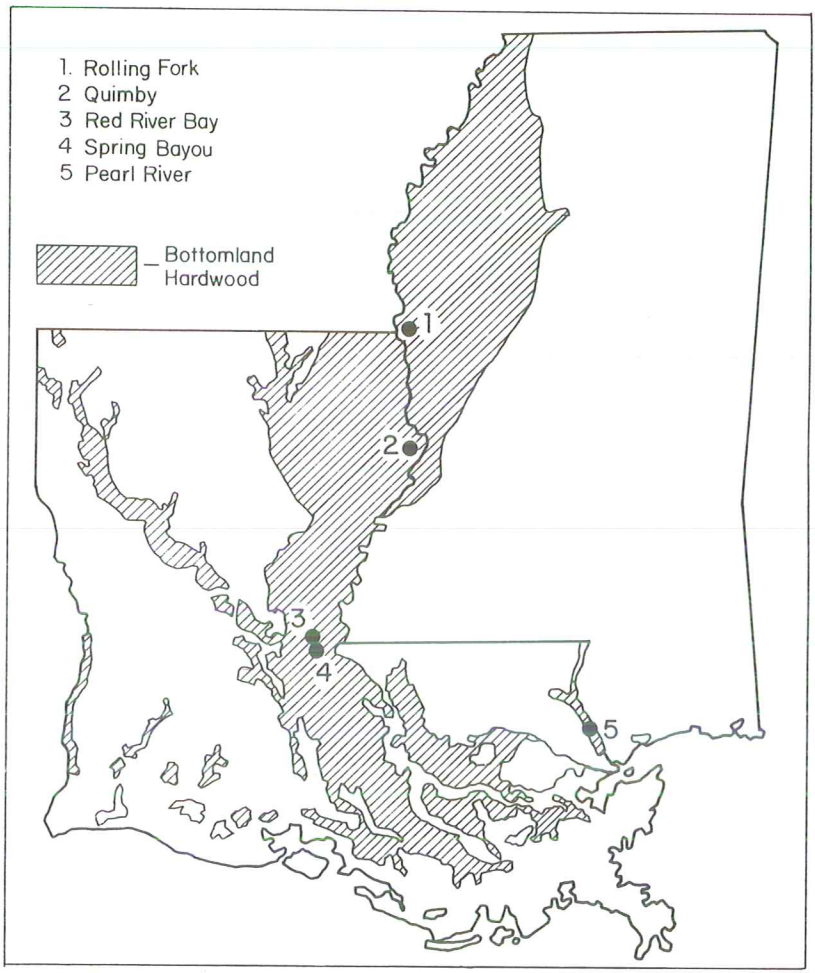
The length of time and the depth to which a soil is saturated are important for soil interpretations, use potential, management, classification, and genesis. A water table strongly influences biological and chemical processes. In most soils, depth and length of saturation can be correlated to the quantity, nature and pattern of mottles relative to soil horizons, and to structure. The relationship between the quantity, distribution, and color of mottles is related to oxidation-reduction conditions in the soil. Periodic saturation of a soil may result in processes of reduction followed by oxidation when the soil becomes unsaturated. Reduction and removal of reduced compounds results in gleying characterized by low chroma colors (15).

Most soils that have repeated or extended periods of saturation are mottled in the wet part of the profile. The abundance, size, and color of the mottles usually indicate the periodicity of saturation. Soils that are predominantly gray with brown or yellow mottles are usually saturated for a much longer time than those that are predominantly yellow or brown with gray mottles. Soils that are never saturated are usually bright colored and are not mottled. Soils that are always saturated during the seasons of biological activity in the soil usually lack mottles and are uniformly gray throughout the zone that is saturated. Mottles may not be visible in some soils because they are masked by the organic matter.

SOILS OF THE STUDY AREA

The study area (Fig. 1) extends from Greenville, Mississippi, to Slidell, Louisiana, a distance of more than 320 km. The Southern Mississippi River Valley is one of the most productive soil areas in the U.S. (1). Most of the valley has been cleared and is used for farming; the remainder of the areas in woodland are usually poorly drained soils subject to flooding. The soils at the Rolling Fork, Quimby, and Spring Bayou study sites are from the Mississippi alluvium and consist of Dundee (Aeric Ochraqualfs), Fausse (Typic Fluvaquents), Tensas (Vertic Ochraqualfs), Tunica (Vertic Haplaquepts), and Sharkey (Vertic Haplaquepts) series. The soils at the Red River Bay study sites are from the Red River alluvium and consist of Fausse (Typic Fluvaquents), Moreland (Vertic Hapludolls), and Norwood (Typic Udifluvents) series. The soils at the Pearl River study sites are from the Pearl River alluvium and consist of Arkabutla (Aeric Fluvaquents) and Rosebloom (Typic Fluvaquents) series.

The character of the parent material controls the texture and mineralogy of most soils formed from it. Almost all the parent materials in the study area are



1. The study area.

fluvial sediments deposited during floods. The kinds of sediments greatly influenced the kinds of soils developed. The sequence of sandy soils along the channels, loamy soils on broad ridges, and clayey soils in the back swamps is common in the study area: Dundee occurs on the broad ridges, Sharkey and Fausse in the back swamps, and Tensas and Tunica in between; Arkabutla occurs on ridges and Rosebloom in swales in the Pearl River floodplains. These are loamy soils from coastal plain deposits from the surrounding Pearl River drainage area. Some of the color characteristics of the soils are believed to be inherited from the parent material. The red color of soils developed in sediments deposited by the Red River are considered relict colors from Permian Red Bed material. These materials seem to resist color change. Soils formed in these sediments

have reddish colors even though they have developed in a climate of alternate periods of saturation. These reddish soils are Moreland and Norwood at the Red River Bay site. Each transect site, soil series, and soil classification is listed below.

Site	Soil Series
	Rolling Fork
1	Dundee
2	Sharkey
3	Tunica
4	Sharkey F.F.
5	Sharkey Dep.
	Quimby
1	Dundee
2	Tensas
3	Sharkey
4	Tensas F.F.
5	Sharkey Dep.
	Red River Bay
1	Norwood
2	Norwood
3	Moreland
4	Fausse
	Spring Bayou
1	Dundee
2	Tensas
3	Sharkey
4	Fausse
	Pearl River
1	Arkabutla
2	Arkabutla
3	Rosebloom
4	Rosebloom F.F.
5	Rosebloom Dep.

Soil classification

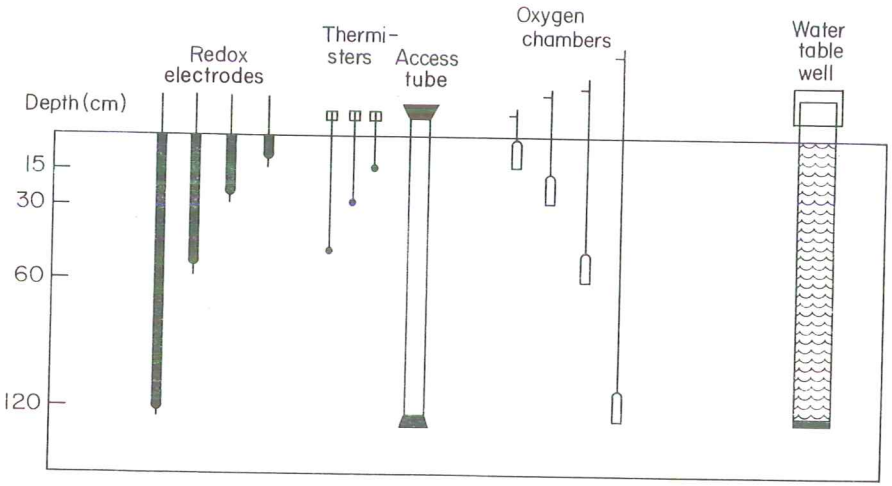
Dundee	-- fine, silty, mixed, thermic, Aeric Ochraqualfs
Sharkey	-- very fine, montmorillonitic, nonacid, thermic Vertic Haplaquepts
Tunica	-- clayey over loamy, montmorillonitic, nonacid, thermic Vertic Haplaquepts
Tensas	-- fine, montmorillonitic, thermic Vertic Ochraqualfs
Norwood	-- fine, silty, mixed (calcareous), thermic Typic Udifluvents
Moreland	-- fine, mixed, thermic, Vertic Hapludolls

Fausse -- very fine, montmorillonitic, nonacid, thermic Typic Fluvaquents
Arkabutla -- fine, silty, mixed, acid, thermic Aeric Fluvaquents
Rosebloom -- fine, silty, mixed, acid, thermic Typic Fluvaquents

MATERIALS AND METHODS

Five transects were selected in early 1982 to study some soil properties along a gradient that extends from nonwetland to wetland. Four or five plots per transect were established to reflect the changes in soil and vegetational characteristics that accompany changes in elevation and soil moisture regime. The transects are located in alluvial bottomlands with mature hardwood forest overstories. The Rolling Fork and Red River Bay transects follow a gently sloping moisture gradient. The Quimby and Pearl River sites have ridge and swale topography, with the latter transect located approximately 0.5 km from the Pearl River. Spring Bayou also follows a generally continual drop.

Each plot (Fig. 2) was equipped with four oxidation-reduction (redox) electrodes (one each at 15-, 30-, 60-, and 120-cm depths), four O_2 diffusion chambers (one each at 15-, 30-, 60-, and 120-cm depths), three temperature thermistors (one each at 15-, 30- and 50-cm depths), one water table well (120 cm deep), and one depth moisture gauge access tube (120 cm deep). This set of equipment was replicated twice on each plot. Soil moisture was measured at 15 30, 60, and 120 cm in depth with a Troxxler model 3222 depth moisture gauge. Because of the gauge's sensitivity to



2. Layout of plot equipment.

hydrogen ions, aluminum access tubes (4.8 cm diam.) were installed to a depth of 120 cm. The tubes were sealed at one end with a number 10.5 rubber stopper and a silicone-based sealant. The access tubes were capped with a rubber stopper to prevent moisture from entering the tube.

Redox potential was measured using permanently installed platinum electrodes. The redox potential at the platinum surface was measured with a battery-operated Orion model 231 millivolt meter and a calomel reference electrode. A hole slightly larger in diameter than the electrode and 2 cm short of the desired depth was made; the electrode was placed in it and set in the last 2 cm with a push rod. A sealing layer of fired clay (to ensure against organic matter contamination) was tamped on top, and the rest of the hole was filled with mortar mix and tamped. The mortar mix draws moisture from the surrounding soil and hardens.

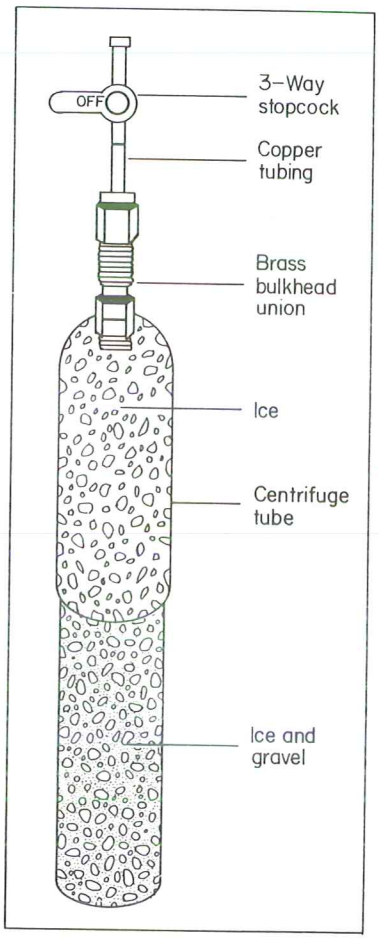
Soil O_2 content was measured with a Yellow Springs model 51B O_2 meter. A method similar to that developed by Patrick (10) was used. Oxygen diffusion chambers were constructed and installed as outlined in Figure 3.

Water table depth was measured in wells established on each plot. Two 7.5-cm diameter PVC pipes with drilled holes to allow water passage were installed to a depth of 120 cm on each plot. A wire mesh screen was attached to the lower end of each pipe to prevent soil from silting in the well from the bottom. A concrete collar was formed around each pipe at the groundline to prevent surface runoff from infiltrating the well.

RESULTS AND DISCUSSION

Monthly sampling was initiated in September 1982, and the results discussed here will include data collected through November 1983. Rainfall was the dominant factor affecting all the transects. Above-average rainfall amounts for the year kept the transects well saturated. Total rainfall through August 1983 ranged from approximately 42 cm above normal (Quimby and Pearl River) to 10 cm above normal (Spring Bayou). Both the Red River Bay and the Rolling Fork transects received about 31 cm of above normal precipitation.

As a consequence of the high rainfall, flooding in the Pearl River Basin and the Red River backwater area was extensive. The lower end of the Rolling Fork transect was also flooded on a regular basis. This caused some damage to the plot equipment and the loss of sampling data points at all three sites. The Pearl River transect was inundated for the entire month of April and no measurements could be taken. The Red River Bay transect was inaccessible in all of June because of backwater flooding.



3. Oxygen diffusion chamber.

Overall plot means

Overall plot means were calculated from the monthly sampling data collected from September 1982 through November 1983 and analyzed as a whole. Each plot contained two replications of measurement equipment, and the plot mean was derived as an average of the readings from both replications. Readings were taken at 15, 30, 60, and 120 cm below the groundline. All plots were numbered in order of increasing wetness, with one being the driest and five the wettest. However, this was based on visual observation, and examination of the data may require the plots to be renumbered. Transect averages were computed by summing across all depths and all plots. Plot averages were computed by summing across all depths.

Soil moisture

There was a general trend of increasing soil moisture from plot 1 to plot 5 for all four depths. This was expected and was the same for all the transects with some minor variations. The driest transect was Pearl River with an average (summed across all depths and all plots) moisture content of 475 kg/m^3 (Table 1). The wettest was Rolling Fork (541 kg/m^3). For the upper end of the transects (plot 1), Red River Bay had the lowest soil moisture content (across all depths) with 375 kg/m^3, and Spring Bayou (450 kg/m^3) and Pearl River (446 kg/m^3) had the highest.

On the lower end of the transects (plot 5), Rolling Fork had the highest (660 kg/m^3) and Pearl River (511 kg/m^3) the lowest moisture content. The highest mean soil moisture content was 689 kg/m^3 at 120 cm on plot 5 at Rolling Fork. The lowest was 368 kg/m^3 at 15 cm on plot one at Red River Bay. There was a distinct break between plots 2 and 3 at Red River Bay. Moisture content increased from an average of 416 kg/m^3 for plot 2 to 557 kg/m^3 for plot 3. No other trends were particularly evident.

Soil oxygen

In general, soil O_2 decreased with increasing wetness (plot 1 to plot 5) and increasing depth. The Quimby transect had the highest mean soil O_2 content (16.0%) and Spring Bayou the lowest (10.0%) (Table 1).

Table 1. Overall soil moisture content, soil oxygen content, and soil redox potential for the wetland delineation transects.

		Soil moisture content (kg/m^3)	Soil oxygen content (%)	Soil redox potential (mv)
Pearl River	Total	475	10.5	352
	Plot 1	446	13.5	419
	Plot 5	511	12.5	273
Red River Bay	Total	484	11.0	305
	Plot 1	375	17.0	547
	Plot 4	585	3.0	24
Spring Bayou	Total	507	10.0	205
	Plot 1	450	13.5	267
	Plot 5	582	6.5	182
Rolling Fork	Total	541	13.5	365
	Plot 1	416	17.5	665
	Plot 5	660	11.0	323
Quimby	Total	525	16.0	393
	Plot 1	436	14.0	635
	Plot 5	615	10.0	98

The highest plot 1 mean O_2 content of 17.5% occurred at Rolling Fork while the lowest (13.5%) was found at both Spring Bayou and Pearl River. Pearl River had the highest plot 5 mean O_2 content of 12.5%. Red River Bay had the lowest with 3%. The highest mean soil O_2 content was 19% at 15 cm on plot 1 at both Red River Bay and Rolling Fork. The lowest was 1.5% at 30 cm on plot 4 at Red River Bay. At Red River Bay, there was a distinct break between plot 2 and plot 3. The average O_2 content for plot 2 was 16%, while the average O_2 content for plot 3 was 6.5%.

Soil redox potential

The soil redox potential followed the same trends as the soil O_2 content -- decreasing with increasing wetness and increasing depth. The least reduced transect was Quimby with an average redox potential of 393 mV (Table 1). The Spring Bayou transect was the most reduced (205 mV). Rolling Fork had the highest plot 1 redox potential of 665 mV and Spring Bayou the lowest (267 mV). A majority of this transect experience reducing conditions (<200 mV). For the plot 5 data, Rolling Fork had the highest redox potential (323 mV) and Red River Bay the lowest (24 mV). These trends are similar to those for the soil O_2 data. The most reduced zone was the 120-cm depth on plot 3 at Red River Bay (-42 mV). The least reduced zone was the 120-cm depth on plot 1 at Rolling Fork (699 mV). These values are comparable to those reported in the literature (2, 9, 11, 12). Once again the same distinct break between plots 2 and 3 at Red River Bay was evident, with plot 3 having a much lower mean redox potential (112 mV) than plot 2 (539 mV).

Spring Bayou was the only transect for which the trends are not really apparent for the transect as a whole, possibly because having more data points for some plots than others (due to high water) caused problems. However, large variations in redox data from platinum electrodes are common as the small platinum tip is susceptible to localized effects and may be in contact with differently aerated zones at the same depth (5, 8). The data for the Quimby transect followed the prevailing trends with some minor differences. There was a sharp decrease in redox potential from the 30-cm depth to the 60-cm depth on plot 3. By contrast, there was an increase in redox potential from the 30-cm depth to the 60-cm depth on plot 4 with a below-ground water table on plot 3.

Water table depth

The general trend for all transects was a gradual increase in water table depth from plot 1 to plot 5.

Some limitations of the current measurement method are becoming apparent. Any water table readings below 120 cm were recorded and analyzed as being 120 cm. This would tend to yield higher mean water table depths than actually occurred. The second problem stems from surface water inundation. When floodwater rises above the ground level, it is recorded as a positive water table depth, inferring that the solum is completely saturated. This may or may not be true. It is probable that complete saturation occurs on the lower ends of Red River Bay and Spring Bayou, while determining the depth of saturation at Rolling Fork and Quimby (plot 4) will require analysis of other parameters such as redox potential and O_2 content where possible.

Mean soil temperature

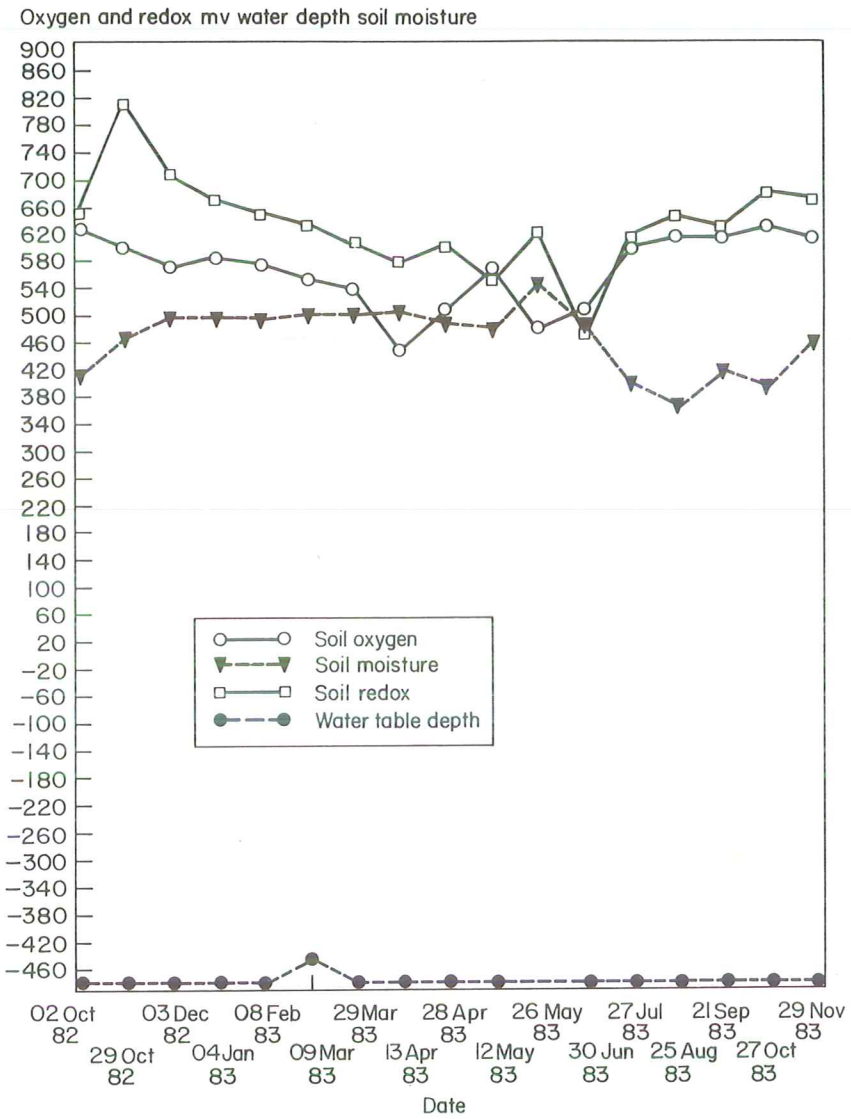
Soil temperature was measured at 15, 30, and 50 cm in depth with a thermistor and permanent temperature probes. Overall temperature means did not show much change with depth or plot, although the wetter plots were slightly warmer. Mean soil temperatures were lower during the wet season and the dormant season. Temperatures were somewhat warmer at 50 cm than at 15 cm and at the lower (wetter) end of the transect for these two seasons. During the dry season and the growing season, a warming trend with increasing plot wetness was the only evident pattern.

Graphs

In an effort to visualize the relationships among soil moisture, O_2 content, redox potential, and water table depth and the seasonal patterns of these parameters, a graphing format was developed by plotting the plot means over time. Figures 4 and 5 show the correlation among O_2 content, soil moisture, redox potential, and the water table. Figure 4 is a dry soil and Figure 5 a wet site. These relationships are similar to those reported by Boynton and Reuther (4), Boynton and Compton (3), and McKeague (9).

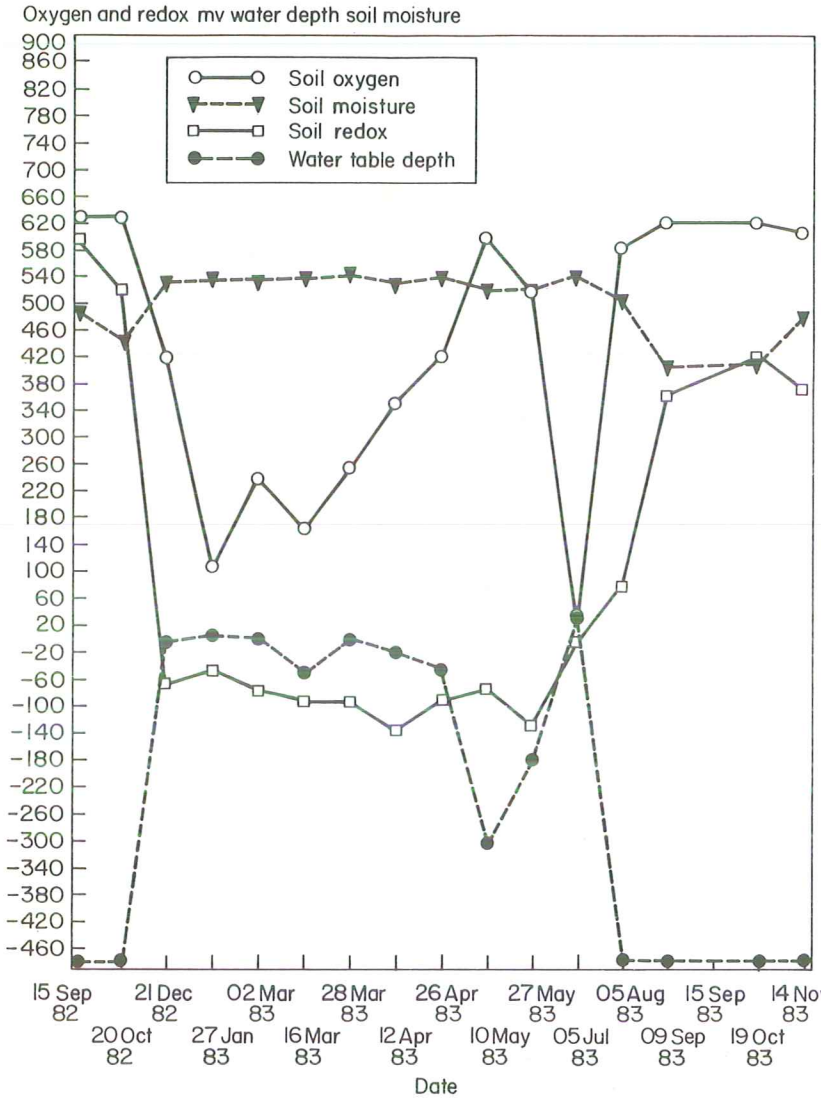
SUMMARY AND CONCLUSIONS

Analysis of the data collected during monthly sampling shows some clear differences in soil moisture regime, soil O_2 content, and soil redox potential. Some of the general trends include: increasing soil moisture from the dry end of the transect to the wet end, decreasing O_2 content with increasing soil moisture and depth, and decreasing redox potential with increasing soil moisture and depth. The highest mean soil moisture content was 689 kg/m^3 and the lowest 368 kg/m^3. The highest soil O_2 content was 19.0%,



4. 15-cm depth oxygen, redox, and soil moisture with water depth plotted over time — Rolling Fork plot 1.

and the lowest 1.5%. The lowest soil redox potential was -42 mV and the highest was 699 mV. Mean soil temperatures were warmer on the wetter plots and during the dry cycle and the growing season. The dry end of the transect was not reduced during the growing season, while the wet end was highly reduced for most of the growing season.



5. 15-cm depth oxygen, redox, and soil moisture with water depth plotted over time — Spring Bayou plot 2.

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ORGANIC MATTER DYNAMICS IN WETLAND SOILS

H. U. NEUE

Organic matter plays an important role in soil formation. It affects directly or indirectly almost all properties and kinetics of the soil. In wetland soils, it is the substrate for anaerobic microbial activity and consequently, in addition to oxygen depletion, the main cause of the characteristic changes in redox potential and pH. The turnover of C in anaerobic soils in the tropics can be almost as fast as in aerobic soils. The low energy-yielding process of fermentation cannot be equated automatically with retarded decomposition.

Inorganic N release during anaerobic decomposition is higher during the first weeks of submergence than under aerobic conditions. Nitrogen release occurs at higher C-N ratios under anaerobic conditions, but remineralization of immobilized N is slower.

In wetland soils, the optimum organic matter content for maximum rice yields seems to be 4-5% depending on the rate of N fertilization.

Soil organic matter plays an important role in soil formation. In wetland soils, it is the substrate for anaerobic microbial activity that results in O_2 depletion and characteristic changes in redox potential, pH, and nutrient availability. The oxidation-reduction processes cause diagnostic properties that are used for classification of wetland soils.

The kind, amount, and distribution of organic matter in the soils determine to a great extent the properties of the diagnostic surface horizons such as the histic, mollic, umbric, ochric, and plaggen epipedons. Illuvial humus and organic solutes play a role in the genesis of the sombric, spodic, and placic subsurface horizons. Organic soils are per se defined by organic materials.

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Though soil organic matter is an important tool for the characterization, classification, and utilization of wetland soils, little is known about the dynamics of organic matter in wetland soils in the tropics.

SOIL ORGANIC MATTER

Soil organic C accounts for 0.1-40% of wetland rice soils. Most mineral wetland soils of tropical Asia have only up to 3% organic matter content, but this amount influences productivity to nearly the same degree as the inorganic constituents. An adequate supply of organic matter is thought to be important in maintaining or increasing soil fertility.

There is no generally valid definition of soil organic matter or humus in the literature. Soil organic matter generally refers to the organic fraction of the soil, which includes plant and animal residues at various stages of degradation, transformation, and neosynthesis, as well as substances synthesized by the soil population. Still in dispute is whether the edaphon itself should be included (20), or if only living cells and tissues of microbes should be added (4). Since organic matter is often analyzed by determining the C content of the fine earth fraction, most parts of the edaphon cannot be separated by this method. Inclusion of the biomass into the organic fraction of the soil can also be deduced from the findings of Paul and van Veen (15). According to them, the biomass holds a unique position among the soil organic matter fractions because it functions as both a sink and a transformation station for nutrients and energy in the soil.

The function of organic matter in the soil is both direct and indirect. Its direct role is concerned with the provision of plant nutrients through decomposition and mineralization (recycling of nutrients). Its indirect role is associated with humification and effects on most of the chemical and biochemical processes, by which the chemical, physicochemical, physical, and mechanical properties of soils are influenced. The main processes that occur in submerged soils can be regarded as a series of successive oxidation-reduction reactions almost entirely mediated by facultative and obligate anaerobic bacteria. Since, aside from inorganic compounds, mainly organic substrates are used as C sources, electron acceptors, and electron donors by anaerobic respiration, the kinetics of reduction and the reduction products in wetland soils are determined largely by the nature and the content of their organic matter.

Soils formed under submerged conditions do not follow a climate pattern as strictly as aerobic soils; temperature is less influential over a wider range, as well as pH, kind and concentration of inorganic compounds, and duration of flooding.

The decomposition -- breakdown to simple organic compounds -- and mineralization -- breakdown to inorganic compounds -- of organic substrates are interrelated with successive microbial changes and are accompanied by a stepwise biochemical and chemical reduction of the soil. As a result, the redox potential of the soil is lowered and the pH changes to near neutral, by which the degradation is further enhanced. Both organic matter and pH/Eh influence rice growth largely by controlling the availability of nutrients, of which only Zn, Cu, and S are affected negatively by submergence.

The stable end-products of decomposition in aerobic soils are CO_2, NO_3, SO_4, H_2O, and resistant residues, but in anaerobic soils they are CH_4, CO_2, H_2, H_2S, NH_3, R-COOH, RNH_2, RSH, and resistant residues. In addition, the anaerobic metabolic processes of bacteria produce an array of substances -- many of them transitory -- not found in well-aerated soils, including gases, hydrocarbons, alcohols, carbonyls, volatile fatty acids, nonvolatile acids, phenolic acids, and S compounds (1, 14, 16, 24).

CARBON TURNOVER

In nature the processes of decomposition, mineralization, and humification (resynthesis and neosynthesis to complex organic forms) are in continual motion. The cycle, including immobilization of inorganic constituents by microbes, is referred to as the turnover cycle. Humification and immobilization retard the turnover, while decomposition and mineralization speed it up. It is possible that these processes balance each other such that there is no apparent change even though the processes are at work (steady state). The magnitude and direction of the processes and their net effects on the amount and availability of the organic matter being decomposed and turned over have been studied by CO_2 respiration measurements and ^{14}C measurements. The latter have been reviewed by Scharpenseel and Neue (18). Since various gaseous and volatile C compounds emerge under submerged conditions, the use of isotopes is advantageous and often absolutely necessary, especially when processes and products should be related to special substrates.

Under anaerobic conditions, both mineralization and immobilization rates are considered retarded. Thus,

the characteristic features of anaerobic turnover are:

- incomplete decomposition;
- low energy yielding of fermentation, resulting in the synthesis of fewer microbial cells per unit of C degraded; and
- lower N requirement of anaerobic metabolism, leading to more rapid release of NH_4^+ even when the C-N ratio is wide.

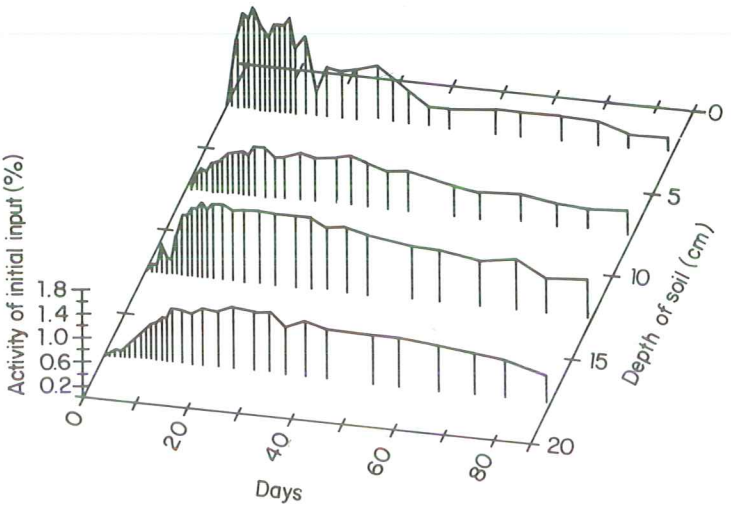
In field experiments we incorporated ^{14}C-labeled rice straw into four depths in an Andaqueptic Haplaquoll on the IRRI farm, Philippines, and kept the soil permanently submerged (Table 1). The topsoil had the following characteristics: pH (KCl) 5.5, 2.2% C, 0.21% N_t, CEC 28 meq/100 g, 99% base sat., 28% clay. Independent of incorporation depth, the soil solution down to the dense layer was contaminated immediately with water-soluble C compounds (Fig. 1). The resulting CO_2 production leveled off after some weeks, while CH_4 formation was maintained. The CO_2-CH_4 production ratio was about 1:3 (26%:74%) after 8 wk, and the activity of the CH_4 in the soil solution accounted for nearly 30% of the mutual input (Fig. 2).

The average of all four treatments of ^{14}C remaining in the soil down to 40 cm was 23.6% after 1 yr (Table 1). In the agronomically important layer (top 20 cm) above the plow pan, the remaining ^{14}C was 18.4%. During the second year, it decreased to 11.5% for the top 20 cm. The decomposition of rice straw slows down with depth of incorporation, showing a marked difference between the top 10 cm of puddled soil and the following layers. Subsequently, water-soluble C compounds that are translocated upward are degraded faster (Table 1).

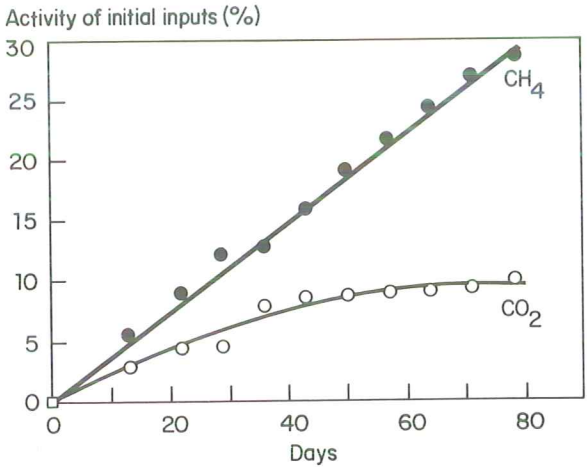
The decomposition pattern in this soil under submerged conditions (Fig. 3) is similar to that observed in upland conditions in Nigeria (8); only the

Table 1. ^{14}C remaining from labeled rice straw 1 year after incorporation.

Depth (cm)	^{14}C remaining in the soil (%) after incorporation at depths of				Av of all treatments down to	
	0-5 cm	5-10 cm	10-15 cm	15-20 cm	20 cm	40 cm
0-5	5-4	3-2	0-8	0-3	18.4%	23.6%
5-10	6.1	4.5	0.6	0.3	↓	↓
10-15	2.0	6.0	9.5	1.6		
15-20	1.1	3.8	10.3	18.2		
20-25	1.3	1.8	4.9	5.2		
25-30	0.8	0.8	1.0	1.1		
30-35	0.3	0.5	0.7	0.7		
35-40	0.3	0.4	0.3	0.5		
Total 0-40	17.3	21.0	28.1	27.9		



1. Activity of the soil solution after incorporation of ^{14}C-labeled rice straw into a soil depth of 5-10 cm. Adapted from Martin (12).

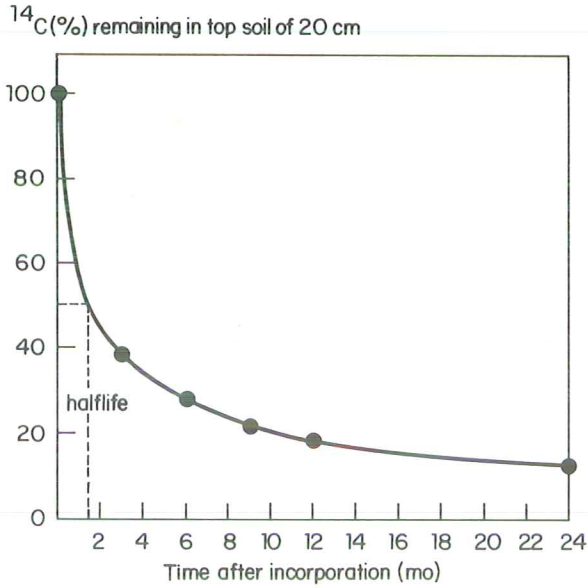


2. Formation of methane and carbon dioxide derived from the soil solution after incorporation of ^{14}C-labeled rice straw. Adapted from Martin (12).

values during the initial 6 mo are slightly less. While the half-life in Nigeria was about 30 d, we found a half life of 43 d.

Drying and wetting the soil, which is the common water regime of rice soils, will enhance the turnover.

These results reveal that decomposition and turnover of organic substrates in submerged soils must not be retarded. If the soil is providing optimum conditions for anaerobic bacteria such as constant temperature of around 30°C, pH 7, high base saturation,

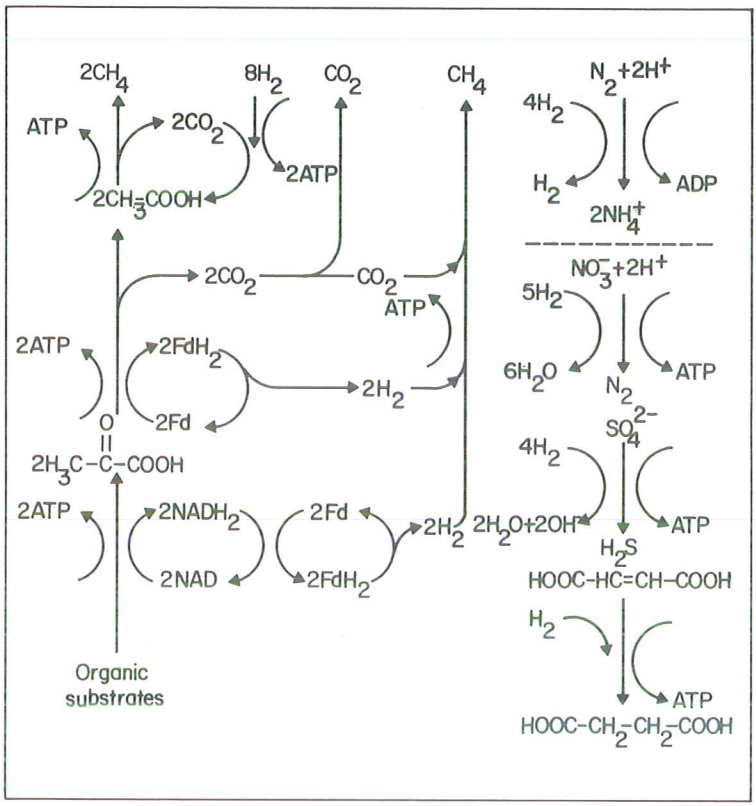


3. Decomposition of ^{14}C-labeled rice straw in a continuously submerged Tropaquept, IRRI, Los Baños, Philippines.

diverse microbial population, and adequate redox potentials, the low energy yield during fermentation and anaerobic respiration has to be compensated for by degrading more substrate, needed as reduction equivalents and H donors, to get an equivalent increase in cell numbers. Figure 4 shows a scheme of anaerobic metabolism and energy transfer. To achieve the degradation to CH_4 and CO_2 and prevent accumulation of intermediate products, a prerequisite is the diversity and successive changes of microorganisms following the food chain of anaerobic degradation. Only a few C compounds have turned out to be resistant to anaerobic degradation: alipathic and aromatic hydrocarbons, steroids, carotinoids, terpenes, fatty acids with more than C_5, and porphyrins (21).

The following factors, gleaned from various sources, retard decomposition of organic substrates (2, 3, 11, 14, 19, 21, 22, 23):

- small supply of C sources and reduction equivalents,
- organic substances rich in lignin and tannin,
- low temperature,
- drought,
- little diversity of microorganisms,
- deficiency of O_2,
- strong acidity,
- decrease of proton or electron donors and acceptors,



4. Scheme of metabolism and energy transfer of anaerobic decomposition.

- increasing salt concentration but decreasing exchangeable Na percentage,
- presence of substrates toxic to edaphon,
- increasing humification,
- high clay content,
- aggregation,
- increasing soil depth,
- burial of organic substrates,
- lack of dense layers,
- zero tillage, and
- low soil, fertilizer, and pest management.

Since the extent and degree of these factors affecting decomposition and its interrelation are not established, there are major difficulties in clarifying these dynamics in an unequivocal way. Findings obtained thus far suggest that the biomass plays a central role in soil organic matter dynamics because it functions as both a sink and a transformation station for nutrients and energy in the soil (15). In wetland rice soils, biomass production in the floodwater and related flood-

water chemistry must have an important impact on soil biomass and organic matter dynamics. If the environment and management practices remain relatively static over many years, the soil organic matter will equilibrate so that gains and losses of C and N will be equal under aerobic as well as anaerobic conditions. Exceptions are some organic soils and lake and marine sediments.

Based on the above decomposition pattern and soil C contents of around 1.7% that have been maintained without addition of organic manures, except roots and short stubble, in long-term trials on the IRRI farm it is estimated that the floodwater is providing a biomass (dry weight) of 1-2 t/ha per season to the soil.

NITROGEN DYNAMICS

Nitrogen is the most important nutrient element in soil organic matter when considered from the economic standpoint. Therefore, the release of NH_4^+ during anaerobic decomposition is extremely important for wetland rice culture.

Crop residues deficient in N decompose just as rapidly with or without added N. Decomposing, they will immobilize any soil N being formed, because microbes are more efficient competitors for N than any crop.

Nitrogen is released from decomposing rice straw at higher C-N ratios under anaerobic than under aerobic conditions. From field studies in California, Williams et al (27) concluded that the N requirement for the decomposition of rice straw in submerged soils is only one-third (0.54% versus 1.5%) the average concentration of N required for aerobic decomposition of residues.

Waring and Bremner (26) observed a more rapid release of inorganic N under submerged than under aerobic conditions. In a 2-wk period, for every one part of inorganic N produced aerobically 1.23 parts were produced in submerged soils.

Accumulation of proteins is always reported greater under anaerobic than under aerobic conditions, perhaps because of the more economic use of N, smaller losses of NH_3, or lesser decomposition of synthesized proteins in the anaerobic system (6). Ammonium ions accumulate in anaerobic soils in contrast to NO_3^- in aerobic soils because nitrification is almost completely suppressed in the former. Nitrifiers are active in the floodwater and in the thin oxidized layer of the topsoil only. As a result, the C-N ratio of almost all mineral wetland rice soils is about 10.

Tusneem and Patrick (25) found that the mineralization rate of organic N of added residues was initially greater under submerged than under optimum moisture conditions. The difference was more pronounced at

higher C-N ratios (>20) and persisted for about 2 mo. Thereafter, the inorganic N still increased under optimum water regime and reached absolutely higher levels, while NH_4^+ accumulation gradually decreased under submerged conditions.

Net mineralization tends to dominate in submerged soils, although immobilization will increase with added residues irrespective of aeration. In greenhouse experiments at IRRI, we found no net immobilization after incorporation of rice straw up to 0.9% by weight in soils with a pH of 5-7 (7).

Tusneem and Patrick (25) found that immobilized N was remineralized slowly under aerobic and even more slowly under anaerobic conditions. Therefore, it is best to fertilize the crop and not the residue or the microbes. While additional N fertilizer often must be supplied in aerobic soils to overcome the immobilization of soil N by large C-N ratios, in submerged soils no extra addition of N is usually required immediately after the incorporation of residues; but at later stages, the addition of N is more needed in submerged soils. Since anaerobic decomposition is mostly done by bacteria that operate most efficiently around neutral pH, anaerobic N mineralization is very sensitive to pH. But mineralization is usually not as limited as expected in adverse pH conditions, because submergence tends to drive the pH of both acid and alkaline soils toward neutral (16). In general, submerged soils therefore have a narrower range of pH values for N release than aerobic soils. In strongly acid soils with a high acidic buffer, as in acid sulfate soils, sufficient pH increase and related N release often can be achieved only by liming. But after the initially enhanced N release, the net mineralization of N seems to decline rapidly in these soils when kept submerged for following crops (7).

VARIABILITY OF FIELD MEASUREMENTS

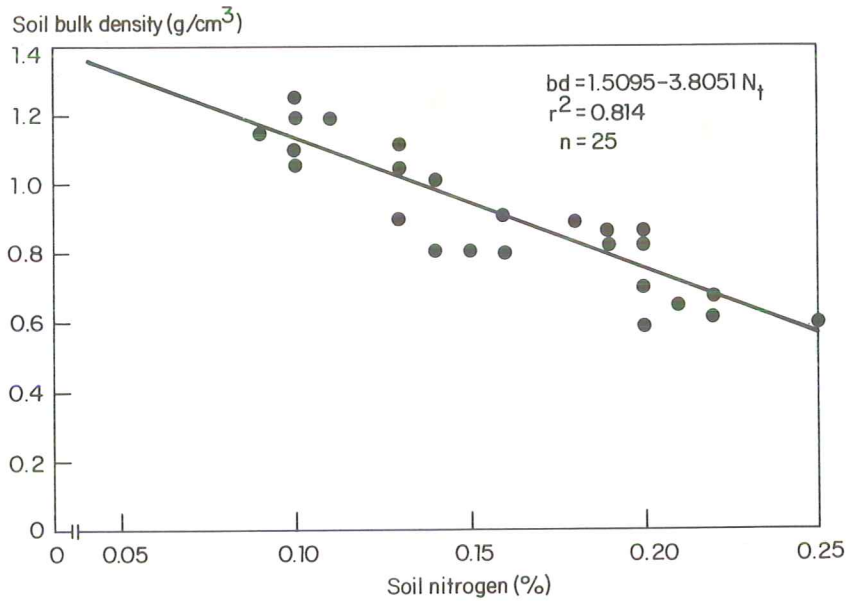
Inhomogeneity is a property of soils (13). The reason for differences in content of nutrients, especially C and N, might very well lie in the inherent variability of soils in the field. Campbell (6) calculated the coefficient of variability for some field experiments to be between 9% and 39%. Two means were regarded as different at the 5% level of probability if the size of their difference was calculated to be about 3.5 times greater when 3 replicates were used than when 10 replicates were used. Thus, large errors in estimating the amount and rate of change of N or organic matter are quite possible if the number of replicates taken is small. This fact has also been emphasized by Kononova

(9) and Cameron et al (5). The latter concluded that, even with as many as 30 samples per field, there was considerable imprecision in values of N and P.

Because of the very intensive cultivation of wetland rice soils, especially when the field is plowed, puddled, and harrowed, the variability might be less in a field than in upland soils, as mentioned earlier. On the other hand, wetland rice soils show great changes in bulk density due to cultivation. In soils with high clay and organic matter content, the bulk density will drop by one half because of puddling.

If the soil is kept submerged, the low bulk density remains or increases slightly over time, related to the biological activity of tubifex, copepods, snails, etc., while removal of the floodwater leads immediately to a sharp increase in bulk density. Timing of soil sampling is therefore highly recommended.

In transforming nutrient contents into amounts, the measurement of bulk density is essential. On the basis of bulk-density measurements of the top 15 cm after final harrowing in 25 mineral wetland rice soils in the Philippines, we found that soil N content is highly correlated with bulk density (Fig. 5). In long-term trials with organic amendments on wetland soils, the horizontal variability of the bulk density, as well as its changes over time, has to be considered.



5. Relation between soil N content and soil bulk density in puddled and submerged soil.

OPTIMUM SOIL CARBON CONTENT

Soils vary considerably in organic matter content (10). The organic C content of mineral wetland rice soils in tropical Asia ranges from less than 0.5% up to more than 8%. The question about optimal soil C content is often asked, but there is no single answer, even for soils from the same climate zone having the same texture.

Aside from other soil-based factors like type of clay and minerals and nutrient level, management practices such as tillage, drainage, irrigation, application of fertilizer, and use of pesticides may make more significant contributions to efficient production than the organic matter level. Furthermore, the best organic matter level is specific to the crop to be grown.

On the basis of yield and N uptake data from long-term fertility trials with N fertilizer rates ranging from 0 to 210 kg/ha on six soils in the Philippines, we developed a significant relationship among grain yield of modern varieties, N fertilizer rate, and organic matter content. The soils (Tropaquepts) had textures from loamy clay to clay and C contents ranging from 0.7 to 3.1%. Since the C-N ratio in wetland rice soils is about 10, the organic matter content can be expressed in terms of soil C or soil N content. The model is based on the following principles and assumptions:

- The mass of soil ($\underline{m_s}$ in kilograms per hectare) is expressed as a function of the soil N content (% $\underline{N_t}$) and the effective root depth ($\underline{d_r}$ in centimetres)

$$\underline{m_s} = 10^5 \times (1.5095 - 3.805\ \underline{N_t}) \times \underline{d_r}$$

- Long-term trials during the last 15 yr revealed that 1 crop of rice takes up to 3.2% of the soil N ($\underline{SN_u}$ in kilograms per hectare) if no fertilizer is applied.

$$\underline{SN_u} = 32\ \underline{N_t} \times (1.5095 - 3.8051\ \underline{N_t}) \times \underline{d_r}$$

- Losses of N fertilizer ($\underline{FN}$) are thought to increase with higher rates. The remaining effective uptake of N fertilizer ($\underline{FN_e}$ in kilograms per hectare) is estimated to be

$$\underline{FN_e} = 1.193 \times \underline{FN}^{0.9}$$

- The attenuation of yield response to N fertilizer ($\underline{FN_a}$ in kilograms per hectare) was found to be

$$\underline{FN_a} = 0.000225 \times \underline{FN_e}^2$$

- Experiments with ^{15}N fertilizer revealed that application of N fertilizer enhances uptake of

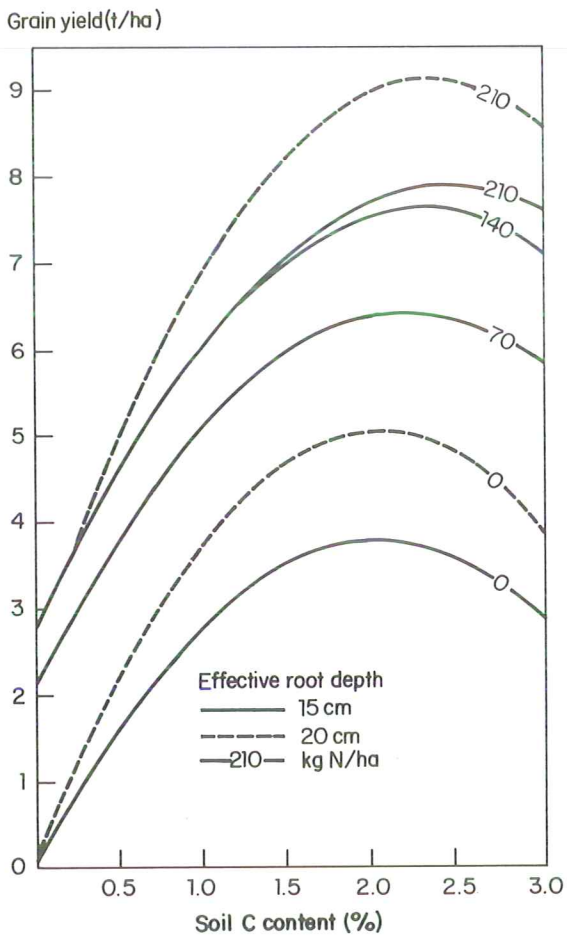
soil N (SN_e in kilograms per hectare). This effect is expressed by

$$SN_e = FN_e \times N_t$$

- Since 20 kg N uptake produces 1 t rice grains, the equation for yield targets (Y_t in tons per per hectare) is

$$Y_t = 0.05 \times FN_e - 0\ 000225 \times FN_e^2 + 0.05\ F\ N_e \times N_t + (2.4152\ N_t - 6.0882\ N_t^2) \times d_r$$

The relationship of target yield to C content and fertilizer rate is shown in Figure 6. Though only data concerning effective root depth (mostly 15 cm for rice), soil N content, and N fertilizer were used, the model worked satisfactorily. Linear correlation of 72



6. Relation among soil C content, N fertilizer rate, and grain yield of rice in puddled and submerged soil.

actual and target yields resulted for different sites in r values higher than 0.839. For organic matter contents below 1.5% and above 6%, the validity of this model has not yet been evaluated. The model not only facilitates determination of optimum yields for given fertilizer rates and soil N contents but also identifies optimum soil N contents by differentiating the yield with respect to N_t. While without N fertilizer, a maximum yield of 3.6 t/ha will be obtained at a N level of 0.20% and 15 cm effective root depth, the optimum level at a fertilizer rate of 210 kg N/ha would be 0.24%. Further increase of soil N seems not to produce higher yields. The increase of rice yields by increasing soil C and N content through incorporation of rice straw has been reported by Ponnamperuma (17).

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TOXICITIES OF WETLAND SOILS

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Toxicity can be defined as the presence of an excessive solute concentration in the soil solution that affects plant growth. Wetland rice soils may have a number of specific toxicities, often induced by submerged conditions. Because of population pressure, more lands with potential toxicity problems have to be cultivated in Asia.

Salinity is a problem in coastal areas with seawater intrusion and in inland areas with excess evaporation. Iron toxicity, which affects acid sandy soils and acid sulfate soils, has often been reported. Its mechanism might be explained by the plant's excessive uptake of Fe^{2+} associated with SO_4^{2-} and Cl^-, which causes acidification inside the plant. Aluminum toxicity is probably the most serious toxicity in acid sulfate soils in Thailand and Vietnam, it damages rice in the early growth stages. Toxicities associated with organic matter occur in peat areas, while H_2S toxicities occur in acid sulfate soils and sandy soils low in Fe.

Extremely high population densities, food deficits, and land scarcity are impelling South and Southeast Asian countries to use areas not really suitable to rice. Among the adverse components of these areas are unfavorable water regimes or soils, or both. Soil problems that had gone undetected are now being explored. These problems include such toxicities as salinity, alkalinity, peat soil conditions, and excess Fe, Al, B, and H_2S.

SALINITY

Soil salinity is defined as the presence of excessive concentrations of soluble salts in the soil. A soil is

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saline when the electrical conductivity (EC) of the saturation extract is more than 4 dS/m (44), the exchangeable Na percentage (ESP) is lower than 15, and the pH is lower than 8.5 (54). Sodium, calcium, magnesium, chloride, and sulfate ions are dominant in saline soils, with NaCl the most frequent cause of salinity. Some young acid sulfate soils may have such high concentrations of $Al_2(SO_4)_3$ and $FeSO_4$ that they also meet the definition of saline soils (32).

Sodic soils are soils with an exchangeable Na percentage over 15. In most cases, such soils also have a pH over 8.5. Saline sodic soils are sodic soils that also have soil-extract EC exceeding 4 dS/m. These commonly have pH values slightly below 8.5.

Occurrence

Soil salinity occurs in two distinctly different regions: in coastal areas where the salinity is caused by seawater intrusion, and in arid or semiarid regions where it is caused by evaporation of the groundwater or surface water.

Marine salinity is confined to areas bordering the seacoasts, situated below the high tide level and not artificially protected (23). The severity of the salinity increases with decreasing rainfall and increasing seasonality of the rainfall. In arid zones, salt accumulation is caused by evaporating seawater, and salt crusts form on the soil surface during dry periods. In equatorial climates, the salt is easily washed away by the high precipitation, either by downward movement through the soil or by lateral surface drainage. The size of the affected area will not change much over the seasons.

Many important rice-growing areas affected by marine salinity are found in deltas in zones with a monsoon climate. Temporary strong salinization is usually caused by saltwater intrusion during typhoons and cyclones.

A major problem in the characterization and classification of coastal soils in marine salinity is the dynamic character of this phenomenon because of the high mobility of the water-soluble salts. Rain can remove salts vertically or laterally, or dilute them to nontoxic concentrations. Salts may concentrate in low places through seepage or runoff, or in high places through evaporation. Microvariability and unpredictability in time and place make agronomic studies on salinity in the field extremely difficult.

Salinization by excess evaporation in semiarid or arid climates affects millions of hectares in places such as India, Pakistan, and the Middle East. The groundwater in such areas need not be saline, but a prolonged upward movement of water with even a low salt content inevitably leads to strong salinity. The

problem has sometimes been aggravated by irrigation schemes, because water tables have moved upward, close to the surface.

Salinization by excess evaporation is found in large inland depressions occupied by lacustrine and illuvial plains or river terraces (23). Inland areas without a pronounced dry climate may sometimes suffer from salinization by interflow, where the source of the salts is salt-bearing rocks at shallow depths in higher parts of the surrounding landscape.

Some young acid sulfate soils have such high EC values that they can be classified as saline soils. The high EC is caused by the oxidation of pyrite, which results in the formation of H_2SO_4. The extremely low pH brings about a breakdown of clays, liberating Al and cations. The soil solution of such soils is dominated by sulfates of Al and other cations. In extreme cases in the dry season, free H_2SO_4 may even be present, while during flooding $FeSO_4$ may become dominant.

Classification of soils affected by salinity

Soil taxonomy (45) distinguishes several groups of soils affected by salinity, but most of them are so strongly saline that (except after reclamation and irrigation) rice growing is impossible. The salinity levels in existing salt-affected rice land are usually too low or at least too variable to be used as diagnostic criteria in Soil taxonomy.

The accumulation of salts in the soil profile is recognized at the great group level. Depending on the kind of salt, the diagnostic horizons are called gypsic (accumulation of gypsum), calcic (accumulation of Ca or Ca/Mg carbonates), salic (accumulation of salts more soluble than gypsum), natric (columnar structure and high sodium adsorption ratio -- SAR -- or exchangeable sodium percentage -- ESP).

Furthermore, Halaquepts are recognized as Aquepts with an SAR over 13 (or an ESP over 15) in the upper part of the profile, but a salic horizon should not occur in any season in arid zones, or should only temporarily occur in other climatic zones. Soils in coastal areas with marine salinity that meet the requirements of Aquepts will often be Halaquepts. They occur extensively in the most recent alluvial areas without sulfidic material in the Mekong Delta. Halic subgroups of other great groups (for example Hydraquents or Tropaquents) can also be found.

A problem arises when a soil does not meet the requirements of the halic subgroup but is affected by salinity, for example, Sulfaquepts with a high electrolyte content and salt efflorescences of $Al_2(SO_4)_3$ in the dry season.

Salinity and rice

Although rice is classified as a moderately tolerant crop, an EC of 6-10 dS/m is associated with a 50% decrease in yield (23, 54). Salt tolerance varies strongly with the growth stage (26, 27) and differs widely among varieties. Rice plants are more sensitive to salt during periods of high light intensity and low relative humidity, and more tolerant during rainy seasons than during dry seasons (23). In those areas where salinity is only a temporary phenomenon, the duration of the saline period is as important as the concentration of the salts.

Symptoms of salt injury in the rice plant are stunted growth, reduced tillering, whitish leaf tips, and, frequently, chlorotic parts on the leaves (4).

Reclamation of saline soils

Where dryland crops cannot be grown because of excess salt in the soil, rice is the ideal crop when the land is flooded with rain or irrigation water, which dissolves and dilutes salts in the surface layer. Ponding of water will induce the process of percolation and drainage. In arid areas with groundwater salinity, a drainage system must be provided to prevent salt accumulation. In monsoon areas, the rainfall may be high enough to provide for sufficient dilution and drainage downwards.

In areas with marine salinity, the most logical solution is protection by dikes. This practice may, however, be very hazardous when acid sulfate soils or potential acid sulfate soils are present. Blocking the entry of salt water will lower the water table during the dry season and cause severe acidification. Brinkman and Singh (4) used salt water to deacidify fishponds in acid sulfate soils. Farmers in the Mekong Delta sometimes flood their fields on acid sulfate soils with salt water, or "fertilize" their land with sea salt before the start of the rainy season to improve the land, and do this quite successfully.

Recent studies in the Philippines have shown that yields can be increased on saline lands by correcting the accessory growth-limiting factors and by using short-duration, salt-tolerant rices in the dry season and intermediate-statured, salt-tolerant rices that have submergence tolerance in the wet season (1, 13, 14, 15). Where salinity is not severe, with good management the new nonlodging, insect- and disease-resistant, salt-tolerant varieties can yield more than 4 t/ha in farmers' fields (15).

IRON TOXICITY

Occurrence

Iron toxicity has been observed in acid soils with a pH less than 5.0 when dry. Iron toxicity may be suspected when a reddish or brown scum of $Fe(OH)_3$ is visible on the soil surface or along cracks, or when a thin oily-looking layer of $Fe(OH)_3$ floats on the inundation water.

Iron toxicity has been identified in three groups of soils. The first one comprises young acid sulfate soils. Soil taxonomy (45) defines the great group of Sulfaquepts as having (besides the criteria for the Aquept suborder) a sulfuric horizon with a pH less than 3.5 and yellow jarosite mottles starting within 50 cm from the surface. When such soils have a high organic matter content in the surface soil, the concentration of Fe^{2+} may reach several thousand mg/litre in the soil solution. This group is known to occur in the Bangkok Plain (47), the Mekong Delta (52), the coastal areas of Malaysia and Indonesia, West Africa (Guinea Bissao, Sierra Leone, Liberia, Senegal), and South America.

Older, more deeply developed acid sulfate soils (Sulfic Tropaquepts) have a sulfuric horizon deeper than 50 cm below the surface and rarely show Fe toxicity. Potential acid sulfate soils (Sulfaquents), characterized by sulfidic material (reduced and containing pyrite) within 50 cm from the surface, are likely to show Fe toxicity after oxidation of the surface soil. Iron concentrations tend to increase with salinity. This presents additional problems for acid sulfate soils in tidal saline waters.

A second group of soils with Fe toxicity is found extensively in Sri Lanka. They are moderately acid sandy soils with low CEC and nutrient status, low to moderate organic matter content (up to 5%), and active Fe up to 0.5% Fe_2O_3. The soils are classified mainly as Tropaquents, Hydraquents, and Fluvaquents and are found in wet valleys. The Fe toxicity is closely correlated with upwelling water by interflow from adjacent acid uplands. According to van Breemen and Moormann (59) interflow may aggravate Fe toxicity by depleting the soil of other nutrients, by inhibiting the formation of a thin oxidized surface layer through the upward movement of water with a low redox potential, and by conveying Fe^{2+} faster than it can be inactivated by oxidation in the roots.

Tanaka and Yoshida (40) also recognized Fe toxicity in what were called lateritic soils, acid to

moderately acid clayey soils, higher in CEC, organic matter, and Fe content than the sandy soils. The toxicity is probably due to low levels of the other nutrients.

Processes causing high iron levels in the soil solution

When a soil is submerged, anaerobic microorganisms start the reduction of soil components with a high oxidation state such as MnO_2 and NO_3^-. Once these are depleted, insoluble Fe^{3+} compounds, often present in the form of $Fe(OH)_3$, are reduced to soluble Fe^{2+} compounds. During this process, organic matter is oxidized, acid is consumed, and the pH rises. In most soils the level of Fe^{2+} increases upon flooding and reaches a peak after 2-5 weeks (29). Concentrations above 300-500 mg/litre occur only in soils with an aerobic pH below 5. In such acid soils, the height of the peak tends to increase with the concentration of reducible Fe^{3+} and the organic matter content. In young acid sulfate soils, particularly high levels of Fe^{2+} tend to develop and often persist for several months. Van Breemen and Moormann (49) attribute this to buffering at a low pH after submergence, which causes the Fe^{2+} to remain in solution, while in "normal" soils the pH rises high enough to make Fe^{2+} precipitate (36).

Iron toxicity and rice

Rice suffering from Fe toxicity may show purplish-brown discoloration called "bronzing" or yellowish to orange discoloration (40). Some varieties, however, fail to show any leaf discolorations, but growth is retarded (17). Growth and tillering are depressed and the root system is scanty, short, coarse, and stained brown or reddish (33). The symptoms are often most clearly seen in the tillering and heading stages. If symptoms appear late, yield is reduced because of sterility.

Iron toxicity has been reported at Fe levels varying between 20 and 40 (48) and 400 mg/litre (9) in the soil or nutrient solution. Generally, the symptoms will appear only at 300-500 mg/litre. At very low levels of other nutrients or in strongly imbalanced nutrient solutions and in the presence of respiration inhibitors such as H_2S, toxicity may appear at 30 mg/litre. Deficiencies of P and K stimulate the uptake of excess Fe (42), but deficiency of N does not (24, 55, cited in 49). Low levels of P, K, Ca, and Mg rather than high levels of active Fe induce Fe toxicity (25).

Iron content of the leaves varies strongly among varieties. Van Breemen and Moormann (49) suggested a comparison of the Fe content of affected and healthy

leaves of the same variety on the same field as a method to confirm suspected Fe toxicity.

Critical levels of Fe toxicity are difficult to establish in plant and soil, and the wide range of critical concentrations reported in the literature makes it questionable whether Fe itself is toxic to rice or is an indicator for other processes that inhibit rice growth.

A possible mechanism behind the iron toxicity syndrome in rice

In acid conditions, Fe concentrations in solution less than about 50 mg/litre have been found to harm rice if nutrient concentrations are very low. At high nutrient concentrations, Fe concentrations up to a few hundred mg/litre are still tolerated. Iron contents in the plants up to 300-600 mg/kg dry matter are generally considered safe. Bronzing, stunting, and other symptoms associated with Fe toxicity syndrome may be observed in rice with Fe contents exceeding these values, but apparently only when soils or nutrient solutions are acid. On neutral soils, very much higher Fe contents, up to a few thousand milligrams per kilogram of dry matter, were found in apparently healthy rice plants that grew well (3). These findings, particularly the last one, are at variance with the assumption that Fe is toxic to rice. Another relatively simple explanation appears to fit all the observed features.

At very low concentrations of soluble Fe, or at moderate concentrations in the presence of adequate concentrations of nutrients, particularly K, Ca, and P, the rice plant takes up no more than the required amount of Fe. When Fe concentrations are high or at high Fe-Ca, Fe-K, or Fe-P ratios in solution, Fe may enter the rice plants in amounts greater or much greater than required. In neutral conditions, the Fe may enter with HCO_3 as the main anion, while in acid conditions, a proportion of the influx of Fe may be associated with Cl^- or SO_4^{2-}. In the leaves, the excess Fe is oxidized to $Fe(OH)_3$. The associated HCO_3^- is converted to CO_2, which is used for assimilation, or it escapes. Any nonvolatile anion, however, will produce the equivalent amount of free acid within the plant. This could be the main reason for the trauma identified as Fe toxicity. If that is the case, any ill effects of excess Fe entering the rice plant would be reduced in proportion to the ratio of HCO_3^- to total anions present.

Amelioration of iron toxicity

Preflooding (to avoid the Fe peak), increasing the O_2 supply in the surface soil by cut-off drains in seepage areas, fertilization (to restore nutrient

balance), liming, and desalinization (to increase the bicarbonate-total anion ratio) are possibilities to overcome Fe toxicity in the various soil types.

Varietal tolerance is a simple and economical solution to Fe toxicity (8), especially for the small farmers of South and Southeast Asia. Several workers have shown that marked differences exist among rice varieties in their tolerance to excess Fe (10, 34, 51). In severe cases of Fe toxicity, tolerant rices gave grain yields of 3 t/ha and 6 t/ha when the disorder was mild (35).

ALUMINUM TOXICITY

Aluminum toxicity on wetland rice soils has not been thoroughly investigated. In wetland rice soils Al toxicity occurs only in very acid conditions. With more pressure to use less fertile land in Southeast Asia, the problem may assume greater importance.

Occurrence

Aluminum concentrations are directly related to soil pH, and toxic concentrations can occur only at pH values below 5. In most acid wetland soils, the pH rises well above 5 shortly after flooding so that Al toxicity is no problem. In acid sulfate soils, the pH rise may be slower, and Al toxicity may occur even after a period of flooding. Aluminum is probably the most important toxin in the acid sulfate soils in the Bangkok Plain (47) and in the Mekong Delta. In both areas, Sulfic Tropaquepts dominate.

Aluminum toxicity may also occur in old, weathered soils such as Ultisols and Oxisols when used for dryland crops. Such soils include the so-called planosols of the lower terraces of the Mekong River, which occur widely in Cambodia and also in the northern part of the Mekong Delta. These soils have been subjected to ferrolysis, a process of seasonally wet soils whereby displaced cations are leached in the reduced period and clay minerals are attacked by acid formed in the dry, aerobic season (2). Although these soils have Al toxicity when used for dryland crops, rice is not likely to be affected, since the planosols are normally flooded when the rice is transplanted so that the pH is generally in the safe range because of soil reduction.

Processes causing aluminum toxicity in the soil

When a potential acid sulfate soil is aerated, pyrite is oxidized to jarosite (which will eventually be hydrolyzed to $Fe(OH)_3$) and H_2SO_4. In noncalcareous soils, the pH drops sharply, clay minerals are attacked by the acid, and K, Mg, Fe, and Al from the clay become

soluble and exchangeable. Young acid sulfate soils contain appreciable quantities of all these cations, and the Al toxicity in those soils is caused mainly by free Al in the soil solution; but in old acid sulfate soils, most of the K Mg, and Fe have been leached downward or transported by the floodwater, leaving a clay with a high Al saturation.

Phosphorus deficiency is associated with Al toxicity because insoluble Al-phosphates are formed, fixing P. Aluminum has a favorable effect on the structure of the soil. Aluminum-saturated clays are very stable, do not disperse, and show a crumb structure.

Aluminum toxicity and rice

Symptoms of Al toxicity are white or yellow interveinal chlorosis of the older leaves; in severe cases the chlorotic parts become necrotic (54). But Al toxicity depresses root growth (12) and may cause harmful effects before it becomes visible in the leaves.

In solution cultures of low pH, Al is toxic to young seedlings at 0.05-2 mg/litre while 3- to 4-week-old plants show toxicity at 25 mg/litre (39, 41). In acid sulfate soils, the type of wetland soil in which Al toxicity most frequently occurs, Al reaches 1 mg/litre at a pH of 4.8 and increases by a factor of 10 for each unit decrease in pH (46). Toxicity in rice is therefore likely to occur at a pH of 4.5-5.0 for seedlings and 3.4-4.0 for older plants, regardless of the type of acid sulfate soil.

Amelioration of Al toxicity

When a Sulfic Tropaquept has a low pH in the topsoil (3.6-4.2), liming can lower or prevent Al toxicity. A rate of 3-6 t is recommended (50), but liming alone proved to be of little benefit on such soils in the Mekong Delta. Phosphorus fertilization at 22 kg P/ha had dramatic effects.

For Sulfaquepts high in soluble Al early plowing right after the recession of the flood is done in the Mekong Delta. This measure cuts off the capillary system and creates a "soil mulch" whereby capillary rise of water and solutes to the surface is inhibited and surface evaporation reduced.

Another measure frequently used in such soils is the "intensive shallow drainage system" (53). Drainage ditches 0.3-0.6 m deep are excavated 9 m apart. The excavated soil is spread evenly over the strip of land between the ditches. Such a system can be used in the early rainy season to promote the leaching of soluble salts from the surface soil. This practice is widely used in areas under the influence of marine salinity and reduces the salinity as well.

TOXICITIES ASSOCIATED WITH ORGANIC MATTER

Peat soils

A classical definition of a peat soil prescribed more than 65% organic matter by weight and a minimum depth of 50 cm (28). Histosols are defined in Soil taxonomy (45) as soils with more than 20-30% organic matter (12-18% organic C) by weight in 40 cm or more of the upper 80 cm of a profile.

The first definition applies to 22 million ha of soils found in Asia (6). Topogeneous peats, or groundwater peats, may be formed in an environment that is relatively chemically rich. In contrast, ombrogeneous peats, formed entirely under rain-dependent conditions, are always chemically poor. The vast majority of tropical peats are well-developed ombrogeneous peats in lowlands and show a characteristic dome shape.

The most important problems posed by ombrogeneous peats are their extremely low nutrient content and often unfavorable physical properties. Even if nutrient deficiencies are overcome by intensive fertilization, wetland rice on ombrogeneous peats often fails to set grain because of male sterility. This is attributed to toxicity of phenols and Cu deficiency (7).

In the peat areas surveyed in the Philippines, rice showed symptoms of NPK deficiency, Zn deficiency, and B toxicity (11, 20). Rice may suffer from salinity, Fe toxicity, H_2S toxicity, and perhaps toxicity of organic substances (31, 40). Unfavorable physical properties are the high pore space associated with low bearing capacity, poor foothold, and subsidence of the land upon drainage.

Deep ombrogeneous peats are unsuitable for wetland rice because of the high reclamation costs, difficult management, and low output. Shallow, topogeneous peats less than 50 cm thick, peaty clays, and peats with a continuous influx of good-quality river water may give good yields. However, when they are located adjacent to deep ombrogeneous peats, drainage water from the central dome may induce the sterility problem (6, 49).

The growing of wetland rice can convert peat lands into productive agricultural soils without costly and destructive reclamation. Millions of hectares of shallow peat soils can be brought under rice if tolerant varieties are grown with N, P, K, and Zn fertilizers (12). Driessen (6) offers some suggestions for overcoming sterility problems, among them draining the peats at the beginning of the reproductive stage and adding Cu compounds.

Toxicities of organic acids

Organic acid toxicity may occur in soils high in organic matter and also in soils into which large

quantities of fresh organic matter (straw or green manure) have been incorporated. Organic acids such as formic, propionic, isobutyric, butyric, isovaleric, and acetic acid are formed upon submergence (43). High concentrations impair root elongation, respiration, and nutrient uptake (54). The concentration of organic acids increases with flooding, reaches a maximum, and decreases to practically zero (30). The organic acid concentration tends to be higher at low temperatures than at high temperatures (5).

The toxicity is due mainly to the undissociated forms of the acids, which prevail at low pH values. There are 10 times more undissociated molecules of acetic acid than dissociated ones at a pH of 3.76 (39). Toxicity levels in the soil solution range between 10^{-3} and 10^{-2} M, depending on the kind of acid, the pH, and the soil temperature.

HYDROGEN SULFIDE TOXICITY

Hydrogen sulfide toxicity in rice was first reported in Japan, where akiochi disease occurs on sandy, well-drained, degraded soils low in active Fe. A critical concentration of about 0.1 mg/litre in the soil solution was reported by Mitsui (22). Hydrogen sulfide concentration as high as 1,200 mg/litre has been detected in a salinized and predried peat soil when the redox potential level reached -180 mV (18).

Hydrogen sulfide in submerged soils results mainly from the reduction of sulfates. Most submerged soils have a low concentration of H_2S because of the formation of FeS, which is insoluble and harmless to the plant. The concentration of H_2S and its dissociated forms H^+ and HS^- vary with pH. The H_2S form dominates in acid soils. Based on chemical equilibria, H_2S toxicity cannot be expected in soils with sufficient Fe^{2+} (29), but Tanaka et al (38) argued that a high production of CO_2 may lead to the formation of $Fe(HCO_3)_2$, liberating H_2S. Dissolved S^{2-} is regulated by Fe^{2+} in equilibrium with amorphous FeS, making presumably toxic levels of S^{2-} possible at pH values below 5.2 even when the Fe concentration is high, for instance, 1000 mg/litre. Such conditions may be present in young acid sulfate soils (23).

Hydrogen sulfide decreases the oxidative power of the roots and induces Fe^{2+} toxicity because the roots are no longer capable of oxidizing Fe^{2+} at the root surface.

When sandy, degraded soils are fertilized, sulfate-containing fertilizers should be avoided. On acid sulfate soils, liming to raise the pH above 5.2 in flooded conditions is recommended.

BORON TOXICITY

Although B toxicity is considered a hazard to crop production in arid irrigated areas (44), in coastal soils (37), and in volcanic areas (19), what is believed to be the first field case of B toxicity in rice was observed on a volcanic ash soil (21). Boron toxicity is now recognized as a growth-limiting factor on soils irrigated with geothermal water or inundated by brackish water (15). Critical soil and plant limits have recently been proposed for rice, and a simple test for B toxicity has been developed (16). Field experiments showed that in the tropics B is easily removed from the soil when low-B water is used.

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PEDOGENESIS OF SOILS WITH AQUIC MOISTURE REGIMES

L. P. WILDING and J. A. REHAGE

The occurrence of soils with aquic moisture regimes is not restricted geographically by specific climatic, topographic, parent material, biotic, or time factors. The only requirement is that the combination of hydrologic and pedogenic processes provides excess water for saturation, sufficient biomass for microbial activity, and sufficient time to effect reduction.

Water, biomass, solutes, and accreted sediments are the major energy and mass gains to aquic soils. Physical and chemical transformations include the formation and destabilization of soil structure, pedoturbation, pH changes, mineral dissolution and synthesis, redox fluctuations, and ferrolysis. Translocations include transport and immobilization of soluble salts, sesquioxides, mineral weathering products, suspended colloids, and organic solutes. Causes of major losses from soils with aquic soil moisture regimes include evapotranspiration; deep drainage; interflow of water; and migration of salts carbonates, and other solutes (e.g., Fe, Al, Mn, and Si).

Reduction and gleying processes that result from biological activity under anaerobic environments constitute only one of the properties diagnostic of soils with aquic moisture regimes (58). Many of the processes in soils with aquic moisture regimes are the same as those for nonaquic analogues. For example, ochric, mollic, umbric, albic, cambic, argillic, natric, salic, calcic, fragipan, and plinthic diagnostic horizons may be found in both aquic and nonaquic soils within a given locale. Furthermore, there is greater similarity among the climatic and edaphic properties of aquic and nonaquic soils within a given geographical area than among all aquic soils collectively (58, 64). For these

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reasons, in Soil taxonomy (64), aquic soils are distributed among the soil orders on the basis of diagnostic properties that persist upon drainage (59).

With the exception of oxidation-reduction processes, the pedogenesis of soils with aquic moisture regimes has not received the same attention as that of better drained analogues (7). Hence, many of the properties and processes in soils with aquic moisture regimes are not well verified. The objectives of this paper are to discuss pedogenic and hydrologic processes and properties common to soils with aquic moisture regimes, to identify problems in the definition of aquic moisture regimes, and to suggest areas where future research is needed.

AQUIC MOISTURE REGIME

Definition

An aquic soil moisture regime "implies a reducing regime that is virtually free of dissolved oxygen because the soil is saturated by groundwater or by water of the capillary fringe" (64). Soils that are periodically saturated throughout the profile belong to aquic suborders, while soils that are saturated only in lower horizons belong to aquic subgroups.

Definition problems

The following problems arise with the definition and taxonomic placement of aquic soils:

- The duration of saturation and anaerobic conditions is not specified.
- The definition requires anaerobic conditions, but low (≤ 2) chroma morphological indices of reduction are based on Fe or Mn (not O_2) reduction.
- There is no quick reliable way to measure O_2 in soils or to verify anaerobiosis under field conditions.
- Measurements of moisture regimes are costly, short-term, and not easily correlated with long-term climatic records.
- The methodology for verifying aquic moisture regimes in high shrink-swell soils poses many problems.
- No provisions are made for identifying surficial saturation versus saturation from below.
- The control section is not specifically defined.

Problems with morphological inferences of aquic moisture regimes

The following are problems associated with morphological markers of aquic moisture regimes:

- Morphological colors correspond more to the duration of Fe reduction than to the duration of saturation (73, 74, 75).
- Inferences assume that Fe-Mn nodules and low chroma colors are contemporaneous and not relict features (51, 53).
- Criteria are heavily biased toward ≤ 2 chroma matrix or ped surface colors, or both.

For example, recent work has shown that: 1) low chroma colors may be present when the soil rarely undergoes reduction, 2) the soil may be anaerobic and reduced but not completely saturated, and 3) soils with chromas of 3 or higher on ped surfaces accompanied by higher chroma ped interiors may be saturated and reduced for short periods (17, 22, 56, 71, 73, 74). However, in these and other studies, the degree of hydromorphism often can be correlated to dominant color patterns among geographically associated soils (18, 20, 38, 43, 69, 70).

PROCESSES CAUSING SOIL SATURATION

Saturation of a soil occurs during periods when water inputs from precipitation and hillslope sources exceed evapotranspiration and drainage. There are two pathways of saturation: development of transient perched water tables and fluctuating groundwater that encroaches upon the solum from a subjacent aquifer. Understanding the distribution, duration, and periodicity of saturation and associated pedogenesis requires an understanding of the following edaphic and microclimatic parameters:

- rainfall amount, intensity, and duration,
- evapotranspiration losses;
- surface structural and vegetative characteristics that affect interception and infiltration;
- vertical and horizontal hydraulic conductivities;
- landscape position including hillslope configuration; and
- antecedent moisture conditions.

One-dimensional numerical simulation models, which incorporate some of these parameters for predicting the occurrence of saturated conditions in soils, have been developed by Boersma et al (4), Bouma (6), Nelson et al (40), and Carbon et al (11).

Two types of groundwater systems, confined and unconfined aquifers, can be distinguished. Confined groundwater aquifers have an upper boundary that is isolated from the solum by an impermeable bed. Water may reach the surface only through springs, fissures, or where streams incise the impermeable bed into the aquifer strata. Unconfined groundwater aquifers satu-

rate the soil either from below when groundwater tables rise or from above by perched groundwater sources that are isolated from the main groundwater aquifer by an unsaturated restrictive layer. Gley and surficial gley soils are not recognized explicitly in Soil taxonomy but are differentiated into many classification schemes based upon whether the groundwater saturates the soil from above or below.

Duration and occurrence of saturation

The duration of saturation and source of excess water affect many important processes in hydromorphic soils, including the intensity of soil reduction, soil reaction, mineral dissolution, translocation of soluble and suspended materials, and accumulation of organic matter. Soil saturation varies temporally and spatially within a geographic region. Soil taxonomy divides this continuum into soils occasionally saturated or nearly saturated (aquic subgroups), those saturated for significant periods of time (aquic suborders), and those constantly saturated (peraquic). The latter is used to describe soils where the water table is constantly near the surface (i.e. tidal marshes, closed depressions, lagoons, estuaries) but is not used as a taxa differentia. Soils and sediments under a peraquic moisture regime are usually reduced except for a thin oxidized zone near the soil-water interface (44).

Groundwater configuration

Soils with aquic moisture regimes commonly occur in lower topographic landscape positions because the groundwater levels are closer to the surface. The groundwater table usually has a relief similar to, but with less amplitude than, the land surface in humid and subhumid regions (10). It will respond more rapidly to water recharge in porous than in fine-textured materials (76).

Saturation by rising groundwater and interflow

Soil saturation from below caused by water table fluctuations is affected by infiltration and lateral water movement (interflow). Infiltration is likely to dominate on flat landforms while interflow dominates on sloping areas. During periods of excess rainfall, periodic saturation of soils in upland basins results from two simultaneous processes: 1) channel expansion and 2) lateral downslope movement of water through the permeable soil mantle. In the advent of a rainstorm, near-saturated conditions develop much more quickly at the hillslope base and gradually move upslope as slopes contribute lateral subsurface flow. The combination of rain falling directly on wet areas and subsurface flow downslope results in expansion of perennial channels

into intermittent channels, depressions, and zones of low storage capacity. After the storm ceases, the channel system and source areas of stormflow recede (13, 42).

Saturation by surface waters

Saturation due to inundation by surface waters is an important process in soils occurring in lowland basins, river valleys, swales, low terraces, and closed depressions. The duration of saturation is determined by the internal soil drainage and the gradient for surface water flow. Rainfall and runoff inputs to the watershed and catchment size influence the availability of floodwater (39).

Formation of perched water tables

There are many types of pedogenic, lithogenic, or artificially induced layers capable of impeding water. Pedogenic layers that have low hydraulic conductivities include fine-textured argillic, natric, petrocalcic, placic, albic, fragipan, and plinthic horizons. Lithogenic layers include hard bedrock, fine-grained or cemented sedimentary rocks, and dense, compacted tills or fluviatile sediments. Tillage and traffic pans are artificially induced restrictive layers. Unless an appreciable slope exists, the excess water in the profile will remain until it is lost by evapotranspiration and slow drainage through the restrictive layer. At a discontinuity between a coarse-textured layer over a fine-textured one, or vice versa, the impedance of saturated or unsaturated flow at the interface creates conditions favorable for reduction and redistribution of Fe and Mn (14). Soil water contents and the degree of gleying generally decrease with elevation above the restrictive layer or horizon (56).

PEDOGENIC PROCESSES AND PROPERTIES

Structural development and stability

Upon desiccation and dewatering of saturated sediments, open fabrics become denser and more compact. Edge-to-edge orientation of clays becomes face to face, and clays become oriented around skeletal grains. Fabric reorientation is in response to contractive capillary water forces pulling particles closer together as water content decreases. Contractual forces exceed tensile strength, and polygonal fractures develop to form very coarse prismatic structures. These prisms subsequently part along bedding planes to form coarse angular or subangular blocky, and thick platy structures (36, 48, 49). Once the new fabric orientation has been assumed, wetting alone without accom-

panying mechanical disturbance does not restore the original fabric or its original high water content (25).

Increasing desiccation-rewetting cycles with increased proximity to the soil surface enhances fabric reorganization and smaller, more stable structural units. Water-stable aggregates in surface horizons are favored by properties common to aquic soils, namely higher organic matter contents, moderate levels of expanding layer clays, and medium to moderately fine textures. In subsoils, decreased organic matter contents, decreased sesquioxide cements, higher shrink-swell potentials, and less well-developed cutanic surfaces on ped interfaces result in larger structural units of weaker grade and decreased stability.

Translocation of soluble salts and carbonates

Classically, aquic soils that have developed from calcareous sediments or parent materials rich in weatherable minerals contain higher salt contents and are more strongly base-recharged than adjacent better-drained upland associates. These soils commonly serve as repositories for salts and soluble products of weathering transported from adjacent uplands by overland flow, interflow, or deeper groundwater recharge. Salt transport and immobilization in hydromorphic soils is dynamic and directly a function of water flux. The direction of water movement can often be inferred from the depth at which salts of different solubilities accumulate in the profile. Salts may be concentrated at the soil surface or at considerable depth in the subsoil or substratum depending on seasonality and mechanisms of water recharge/discharge. In depressional landforms, central areas may be strongly leached while slightly elevated mounds or perimeter rim positions have salts and carbonates concentrated near the soil surface by evaporative capillary pumping (50, 60). Soils that undergo acid weathering under alternating redox conditions commonly have lower base status and lower salt contents in E horizons but higher base status, salt contents, and even carbonates in lower horizons.

Organic matter accumulation

Soils with aquic moisture regimes, especially at higher latitudes and altitudes, have higher organic matter contents because rates of decomposition are reduced by cooler soil temperatures, anaerobic conditions, and toxic substances (sulfides and some biological exudates). Rates of organic matter accumulation, chemical composition, and susceptibility of organic matter to microbial decomposition have been recently summarized by Everett (21) and Ugolini and Edmonds (63). Under

conditions very favorable for organic matter accumulation mineral soils have histic epipedons and are associated with Histosols. In subsoils, organic matter contents decrease markedly to levels that may be insufficient to sustain microbial activity. Organic matter in subsoils may be of higher charge and strongly bonded to clay mineral surfaces (19, 79,).

Translocation of organic solutes

McKeague et al (33) have recently reviewed the role of organic solutes in pedogenesis of Aquods with placic or indurated (ortstein) horizons. Organic solutes serve as a labile energy source for microbes, as an effective mineral weathering agent, and as a chelator of Al and Fe, enhancing translocation of these elements. Low molecular weight and highly acidic fulvic acids with carboxyl, carbonyl, and phenolic functional groups are apparently responsible for cheluviation. Although the role of organic solutes as organic complexing and weathering agents is widely reported, the precise mechanism and valence state in which the metals are complexed are still under debate. Immobilization of the organic chelation complexes is most likely by supersaturation of the complexing agent with metals or sorption to Al and Fe oxides. Many other hypotheses have been offered, including immobilization at the interface with a water table.

Pedoturbation

Faunalturbation (61, 75), floralturbation (2, 52), and cryoturbation (77) are important though often underemphasized processes in soils with aquic moisture regimes. Soil mixing by crayfish is one of the most dynamic soil processes in Aqualfs and Aquolls; the resulting krotovina are devoid of structural porosity and reduce infiltration, hydraulic conductivity, and water recharge to subjacent horizons (73, 74, 78).

Treethrow causes hummocky topography, which favors development of aquic moisture regimes in microlows. Wet soils and restrictive subsurface layers (argillic, fragipan, spodic, placic, and permafrost) limit depth of rooting and contribute to treethrow. The spatial variability of physical and chemical soil properties and plant communities is markedly enhanced by treethrow (31, 32). Soils that undergo seasonal freezing are highly subject to formation of lenticular ice, ice wedges, frost heaving, pattern ground, and moisture transfer by vapor-flux.

Redox transformation

Chemical processes in soils with aquic moisture regimes are dominated by soil reduction or by alternating cycles of oxidation and reduction. Chemical and

mineralogical transformations associated with gleying are largely related to the fate of Fe, and secondly Mn, although many other chemical processes such as phosphate and trace element mobilization are also characteristic of seasonally or permanently saturated soils. The following brief review of oxidation-reduction (redox) transformations emphasizes processes important in the genesis and resulting properties of soils developed under aquic conditions. Recent articles by Ponnamperuma (46) Patrick and Mahapatra (45), van Breemen and Brinkman (67), and Bohn (5), and other papers in this volume provide more comprehensive summaries.

Redox environments. Soil reduction will take place only when three conditions are met simultaneously: 1) presence of an organic matter supply, 2) absence of an O_2 supply, and 3) presence of anaerobic microorganisms in an environment suitable for their growth (7). The requirement that O_2 be absent is contingent upon the interstitial pores being full of water because, when saturated, chemical and microbial demand for O_2 greatly exceeds O_2 resupply so that the soil becomes anaerobic within a few hours or days (62). Under anaerobic conditions, the sequential reduction and mobilization of N-, Fe-, Mn-, and S-containing compounds occurs because the oxidized forms of these elements serve as electron acceptors in the metabolic processes of facultative anaerobic bacteria (46). Oxidation processes follow the reverse sequence.

Soil acidity plays an important role in redox reactions in soils. The slope of the Eh/pH boundaries separating redox couples in a stability field diagram demonstrates that much more intensive reducing conditions (low Eh) will be necessary to dissolve Fe and Mn in alkaline soils compared with acid soils (16, 23).

Greenland (24) suggested that a heterogeneous distribution of available organic C and active microbial populations may contribute to numerous anaerobic microzones in predominantly aerobic soils. Photochemical indicators of reduced Fe such as α,α'-dipyridyl (12) or orthophenathroline are potentially useful markers for locating microzones of Fe reduction.

Mobilization and immobilization of iron and manganese. Alternating oxidizing-reducing conditions result in the release of Fe and Mn from primary minerals and their segregation into mottles and concretions in the weathering profile. In soils with restricted drainage, maximum concentrations of sesquioxides in the form of mottles, sesquans, nodules, and petroferric materials generally occur near the depth of the upper boundary of a fluctuating water table (26, 29). Mobile Fe^{2+} and Mn^{2+} ions diffuse upward from reduced zones in response to a concentration gradient and precipitate as relatively insoluble oxides or

oxyhydroxides in the capillary fringe above the water table (27, 54). Under the combined influence of a transient perched water table and a leaching regime, Mn compounds commonly accumulate below the zone of Fe immobilization. Diffusion may also occur laterally across peds in response to concentration or Eh gradients, or both.

Periodic oxidation and drying appear essential for nodule formation. The absence of nodules in deep horizons of hydromorphic soils may be ascribed to continuously moist conditions, which retard the dehydration and crystallization of Fe or result in complete translocation of the mobile forms from the solum (37, 55).

Plinthite and indurated sesquioxide nodules or sheets commonly occur in soils on old geomorphic landforms that have been subjected to alternating redox conditions. In order for petroferric materials to accumulate in these systems, the period of saturation should be sufficient to cause reduction, but not so long that the dissolved forms are lost from the system by diffusion or leaching (68). The occurrence of plinthite and petroferric layers is apparently associated with either present or relict alternating redox conditions, although the specific processes involved in their segregation, induration, and transformation are still uncertain.

Macroporosity and morphology. Macropores have a marked effect on redox potentials because they drain freely under low suction and often have an O_2 status similar to that of the atmosphere above the soil surface. Under very wet but unsaturated conditions, ped surfaces tend to be aerobic, while a few millimetres within the aggregate the soil matrix remains anaerobic (28). Soils that remain near saturation for long periods are characterized by low chroma ped interiors with high chroma ped and channel cutans. Reduction within peds causes diffusion of soluble Fe and Mn from the soil matrix to the more oxidized structural surfaces, where precipitation occurs as ferrans and sesquans (7). Soils that are saturated for very short periods (a few days or less) may experience reduction of Mn but not of Fe. In these systems, the soil matrix retains a high chroma but dissolved Mn diffuses toward aerated ped surfaces, precipitating as ped and channel mangans (70). Soils with little or no free-Fe oxides or weatherable mafics may have low chroma colors that do not change upon oxidation or reduction.

In pedal soils water preferentially flows along a system of vertical, interconnected voids initially bypassing ped interiors (7). The size, continuity, and proximity of macropores markedly affect redox potential dynamics (72). Soil materials adjacent to structural surfaces will likely respond much more quickly to redox

potential changes than will the interior of aggregates; this is probably due to reduced diffusivity of gases and transport of solutes across the ped-void interface. Restricted lateral flow into, and preferential flow around peds often results in albic neoskeletans along ped surfaces that contain less clay, lower sesquioxide contents and lower chromas than the adjacent soil matrix (74). Their occurrence is more closely related to the duration of Fe reduction than the period of saturation. Other markers of active reduction include cutans and mottles of blue, green, or gray colors along old root channels and on faces of structural aggregates (30). In such microzones of organic matter decay, sulfate and Fe^{3+} may be reduced to immobile black ferrous sulfides (3).

Soil reaction. The overall effect of submergence is to increase the pH of acid soils and to depress the pH of alkali and calcareous soils. Reduction of Fe^{3+} oxides and oxyhydroxides to Fe^{2+}, along with an attendant increase in alkalinity, results in a pH rise, especially in initially acid soils (46). In alkali or calcareous soils, less dissolved Fe^{2+} and hence less HCO_3 are formed. Under waterlogged conditions, microbial activity leads to accumulation of CO_2, which has an acidifying effect on Na_2CO_3-H_2O-CO_2 and $CaCO_3$-H_2O-CO_2 equilibria (47). In highly buffered systems, the pH stabilizes around 6.5-7.0 unless organic matter is limiting; in some alkali systems low in organic C (<0.4%), the pH rarely drops below 8.5 (39).

Under a periodically saturated regime the alternating oxidation and reduction of Fe can lead to soil acidification. The process of "ferrolysis" has been described by Brinkman (8) for explaining the formation of gray, degraded horizons having low clay contents and very low cation exchange capacities developed under aquic conditions. The effects of ferrolysis are expressed most clearly in soils derived from sediments or rocks containing low contents of weatherable minerals where saturation is mainly by impounding rainwater (39). During anaerobic periods Fe is reduced along with oxidation of organic matter and production of alkalinity. Ferrous iron replaces part of the exchangeable cations; these cations are removed as soluble bicarbonates if hydrological conditions are suitable. During the following aerobic phase, unneutralized H^+ formed by oxidation will lead to acidification (65). Saturation of clays with H^+ causes spontaneous release of Al from octahedral positions in clay minerals (15); this leads to the formation of soluble polynuclear Al species and silica at the expense of clay minerals, especially those of high layer charge. Part of the Al will migrate out of the profile, but a portion will likely occur as exchangeable Al or be precipitated as interlayers in smectitic clays (9). Interlayer hydroxy

Al decreases expansion of 2:1 clays, increases phosphate and sulfate adsorption, increases pH dependent charge and buffering capacity, and decreases K^+ fixation (34). Ferrolysis would not likely occur in carbonate-rich soils or in soils receiving ample amounts of basic salts with flood or interflow waters (39).

Acid sulfate weathering caused by the oxidation of metallic sulfides upon drainage of tidal flats rich in organic matter has been described by van Breemen (66) as another mechanism to increase the acidity of aquic soils.

Translocation of clays

Many soils with aquic soil moisture regimes have strong textural differentiation between surface and subsoil horizons. While this phenomenon has often been attributed to the illuviation of clay into finer textured subsoils, other mechanisms such as sedimentary discontinuities, ferrolysis, in situ weathering of primary minerals and lithorelics, neoformation of clay, and differential transport of eroded sediments have also been advanced. It is probable that the magnitude of translocated clays in sola of aquic soils has been much overestimated (33, 57). Apparently bleached ped coatings, organic films, and pressure faces are frequently misidentified as clay films when ped surfaces are examined in the field before drying.

High organic matter contents, water stable aggregates, high levels of polyvalent cations, low hydraulic gradients, and a lower frequency of desiccation-rewetting cycles do not favor significant dispersion, suspension, and translocation of silicate clays from the A to the B horizons in most aquic soils. High shrink-swell activity and ped instability in subsoils would deter the formation of illuviation argillans or destroy preexisting ones (41, 57).

Aquic and aeric intergrades to Alfisols and Ultisols may have sufficient translocation of clay into lower subsoils to plug macropores, decrease permeability, and seasonally perch water. Translocated materials become finer textured with depth (35). The upper sola of these soils are most acid; redox, Fe-Mn segregation, ferrolysis, and development of albic materials are dynamic processes occurring at the interface with restrictive layers. These soils commonly exhibit bisequal horizonation and are recognized as surficial gleys or pseudogleys in many classification systems.

Transformation of clays

The full range of clay minerals occurs in aquic soils. Aquolls and Aqualfs that form in base-rich environments generally have higher smectite contents than better

drained upland associates (1). This is attributed to their less intense weathering regimes or to a favorable base-rich and silica-rich environment for neoformation of smectite, or to both (19). While some Aquox, Aquepts, and Aquults follow similar trends, more stable kaolinite and pedogenic chlorite are likely to predominate in these soils.

Development of albic horizons

One of the most prominent and distinguishing characteristics of soils with aquic moisture regimes is the development of albic horizons and albic neoskeletans on ped surfaces (7, 73, 74). Eluviation of pigmenting and cementing compounds such as organic matter, clay, and sesquioxides results in uncoated skeletal grains and loss of cohesive strength within peds. With ped destabilization, slaking and translocation of suspended fine silts and clays to lower horizons occur. Immobilization of translocated materials takes place along macrovoids. With progressive intensity of albic horizon development, macrovoids in lower horizons become further plugged with clay and sesquioxides while residual albic materials occur as skeletans, interfingering or tonguing. Eventually this process may cause formation of impermeable subsoils and seasonally perched water tables accompanied by acidification, mobilization, and resegregation of sesquioxides and further degradation.

FUTURE WORK

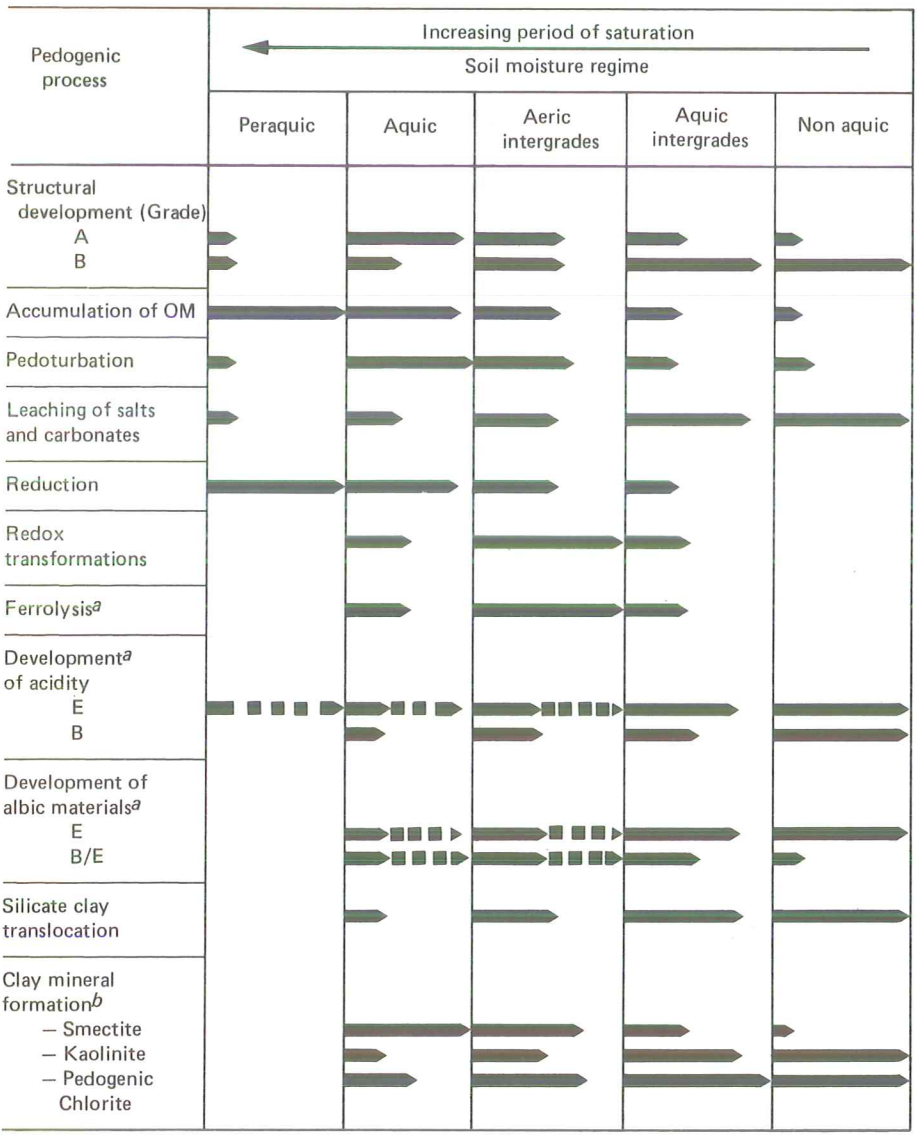
The following suggestions represent areas of research that would further elucidate pedogenesis, behavior, and management of aquic soils and their taxonomic placement.

- Evaluate the relationship between duration and periodicity of soil saturation and intensity of soil reduction.
- Determine the microsite variability in soil redox potentials with respect to macromorphological and micromorphological features.
- Develop rapid field methods for the verification of O_2 depletion and Fe-Mn reduction in soils.
- Identify morphological markers of contemporaneous soil moisture regimes in widely different physical, chemical, and mineralogical conditions.
- Determine the reaction dynamics, including chemical and biological thresholds, which control dissolution and redistribution of sesquioxides, pH changes, and mineral transformations in soils.
- Verify current hydrological models and develop new approaches for predicting the occurrence and

duration of soil saturation under varying climatic, soil, and hydrologic conditions.

SUMMARY

Figure 1 schematically illustrates the relative intensity of selected pedogenic processes active in soils



[a]Pertains primarily to acid environments. [b]Smectite – base-rich environments; kaolinite and pedogenic chlorite – acid environments.

1. Relative intensity of pedogenic processes as a function of saturation duration. Intensity of each process is proportional to bar length. Dashed bars reflect highly variable weathering processes.

with different periods of saturation. The authors fully recognize that there may be many exceptions to these generalizations. The illustration is an attempt, however, to relate the magnitude of processes among various soil moisture regimes. It suggests that accumulation of organic matter and soil reduction increases with duration of saturation; with the exception of peraquic conditions, pedoturbation, formation of smectite in base-rich environments, and structural development of A horizons follow this same trend. In contrast, structural development of B horizons, leaching of salts, development of acidity, development of albic materials, clay translocation, and formation of kaolinites and pedogenic chlorites intensify with decreasing periodicity of saturation. It is proposed that intensity of redox transformations, ferrolysis, development of acidity in E horizons, and development of B/E horizons are greatest in aeric intergrades to aquic moisture regimes (in base-poor environments) because of the higher frequency of redox fluctuations in these soils.

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CHARACTERIZATION

MORPHOLOGY OF WETLAND SOILS

H. P. BLUME and E. SCHLICHTING

Wetland soils are characterized by hydromorphic features (halomorphic, gypsimorphic, calcimorphic, or redoximorphic ones, depending on the volume of the catchment area), whose arrangement corresponds to differences in redox or water potentials in space and to their changes in time. The morphology of typical wetland soils, especially those in central Europe, is described following the system of the German Soil Science Society. Subhydric soils differ in the nature of their organic F horizons between the lakewater or seawater and the reduced mineral material (Gr). In groundwater soils Fe and Mn oxides occur towards the surface of the peds and the soil, whence the oxygen comes, whereas in surface water soils the opposite holds true, since reducing organic compounds come from the surface. Groundwater soils are differentiated according to depth of occurrence and thickness of the oxidized Go over the reduced Gr horizon, which depend mainly on mean levels and fluctuations of groundwater and on texture. Correspondingly, surface water soils differ in degree of bleaching of the Ag horizon and of the ped surfaces in the underlying Bg horizon, which depends mainly on climate and on differences in hydraulic conductivities in both layers. In stratified or in slope soils, or in both, groundwater and surface water phenomena may occur side by side.

In wetland soils, water containing dissolved ions and gases fills even the macropores over time. Where the macropores border on the atmosphere or on pores filled with air, gases are exchanged according to the concentration gradient. This gradient will be sufficiently high for a substantial loss of water only if large pores or a dry atmosphere, or both, border the macro-

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pores, whereas the air always contains so little CO_2, even less CH_4, and so much O_2 that these gases can be exchanged efficiently with the air even in medium and small pores. Provided the catchment area supplies the formation of evaporates (e.g., simple salts, gypsum), loss of CO_2 causes decarbonation leading to precipitates (e.g., lime), and gain of O_2 causes oxidation leading to oxidates (e.g., Fe or Mn oxides or sulfates) near the zone rich in reductates (e.g., Fe sulfides, organic matter) and saturated with water. Thus, wetland soils are characterized by one or more of these hydromorphic features.

Hydromorphic features often coincide with but are not identical to redoximorphic features (e.g., Fe^{2+} sulfides and Fe^{3+} oxides). Wetland soils may lack redoximorphic features, as when the soil water is rich in O_2 or poor in organic matter (e.g., upper floodplains with coarse texture, desert environment) and -- vice versa -- dryland soils may be redoximorphic, as when the parent material is rich in reductates (e.g., shales, mudstones) or the soil air contains much CO_2 or CH_4 that excludes or consumes O_2 (e.g., over postvolcanic mofettes or landfills with town wastes). Here we shall deal only with hydromorphic and redoximorphic features.

While the kind of compounds formed depends mainly on the nature of the catchment area, the arrangement of the hydromorphic features is related to differences in redox or water potential in space as well as to their changes in time, and thus to the distribution pattern of air and water. The following types of water saturation can be distinguished:

- permanent and total saturation = submerged soils
- temporary and total saturation = floodwater soils
- permanent saturation in the subsoil = groundwater soils
- permanent-temporary saturation in the topsoil = surface water soils.

This water may be stagnant or interflowing down slopes or alluvial plains. In floodwater soils, seasonal flooding by rivers has to be distinguished from diurnal flooding by the sea, which scarcely allows aeration between tides.

We shall describe and explain the morphology of typical wetland soils, especially those in central Europe. We follow the taxonomy and nomenclature of the German Soil Science Society (3, 4), since it differentiates more according to hydromorphic features than most systems. Occasionally we try to classify according to Soil taxonomy (9) as well. Concerning definitions of and symbols for diagnostic features and horizons, we follow our own proposals (7).

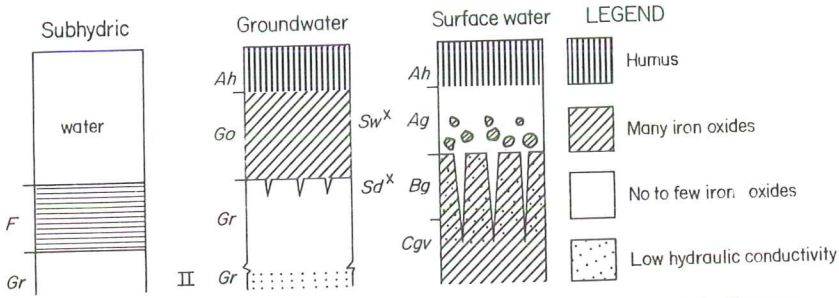
SUBSOILS GROUNDWATER, AND SURFACE SOILS

Wetland soils can be classified according to fundamental differences in the arrangement of their hydromorphic features as subhydric, groundwater, and surface water soils (6, Fig. 1).

The typical subhydric soil is permanently wet. Between the lakewater or seawater and the Gr horizon, there are humic F horizons of various thicknesses (muds). In dystrophic lakes the muds consist entirely of black-brown organic matter rich in colloidal substances, and this horizon (Ff) is diagnostic. In mesotrophic to eutrophic lakes with a hypolimnion containing O_2, the F horizon (Fh) typical for the Gyttja (Table 1) has an olive color ("liver mud"), Eh>200 mV, and pH ≅ 7. In hypertrophic lakes and tidal swamps, we find the Sapropel, characterized by a black F horizon (Fr) with E_h<200 mV and pH>7, normally containing H_2S.

In the typical groundwater soil, the subsoil is permanently wet (Gr). In loams to clays it is blue-green because of Fe^{2+} and Fe^{3+} hydroxy salts ("green rust"); in material rich in S it is black because of Fe sulfides; in carbonate-rich material it is white because of calcite or siderite; and in sands it is light gray to white (Munsell: N1-N8, 5Y, 5G, or 5B) and often low in Fe and Mn. In the upper Gr, up to 5% rusty colors may appear, mainly around animal channels or the roots of swamp plants.

In the capillary fringe and in the topsoil (Go), however, the reddish brown of ferrihydrite or the bright yellowish brown of goethite are predominant. In loams to clays the Fe oxides are concentrated on aggregate surfaces and the walls of larger pores like former root channels (which in extreme cases are entirely filled with such oxides), whereas the cores still have Gr colors, especially in the lower Go. Thus, the distribution pattern of the Fe and Mn oxides is "extrovertly" oriented toward the ped and the soil surface, from where the O_2 originates.



1. Archetypes of redoximorphic (hydromorphic) soils and nomenclature of the German soil survey.

Table 1. Extract from the German system of soil classification (adapted from Muller 1982; designation of horizons according to Schlichting and Blume (7).

1. Terrestrial soils (order
   Mineral soils without periodic flooding or influence of groundwater in the upper 40 cm
1.10 Surface water soils (suborder)
   Soils with redoximorphic surfacewater features (*g*) *g* ("marbled") = diagnostic feature of a mineral horizon influenced by soil water stagnating and/or bound in capillaries near the surface (above 130 cm) with the following characteristics:
   1. temporarily poor in O_2 and rH ⩽19 (unless drained) *and*
   2. a) bleached (value ⩾4, chroma ⩽2.5) with Fe and Mn concretions *or*
      b) marbled (>80% by area), i.e. surfaces of aggregates bleached (like a) and cores partly rusty.

1.10.1 Pseudogley (Stauwasserpseudogley) (type)
Surfacewater soils with pervious layer
(kf mostly >10 cm/d) over pervious layer
(kf mostly < 1 cm/[b])

Typischer Pseudogley: *Ah–Ag–Bg* (–*Cg*)–*C* (>30 cm) — *Sn*

Kalkhaltiger Pseudogley: *Ah–Cg*, calcareous throughout the profile — *Sc*

Hangpseudogley: as Sn, slope >9% — *Sg*

Anmoorpseudogley: *HA* (15-30% org. subst.)–*Ag–Bg* (>10 cm) — *Sa*

Braunerde-Pseudogley: *Ah–Bv* (<40 cm) –*Bg*–II*Bg* (kf<1) or *Ah–Bvg*–II*Bg* (kf<1) — *B-S*

Parabraunerde-Pseudogley: *Ah– (Al)–A1g–Btg* (<40 cm) — *L-S*

Podsol-Pseudogley: *Aeh–Ae–Bhs–Bg*–II*Bg* (<40 cm; kf<1) — *P-S*

Pelosol-Pseudogley: *Ah-Bag* (or *Cag*)–II (*Bag-*)*Cag–C* (kf<1) — *D-S*

Chernozem-Pseudogley: *Ah–Agh–Ahg–* (*Cg–*)II*Cg* (<40 cm; kf<1) — *T-S*

Plaggenesch-Pseudogley: *Ah–pD–pDg-* (*Bg–*) II*Cg* (<40 cm; kf<1) — *E-S*

Gley-Pseudogley: *Ah–Ag–Bg* (kf<1) –(*Go-*)*Gr* (40-80 cm) — *G-S*

1.10.2 Haftnassepseudogley (type) — *SH*
Surface water soil with capillary water horizon (*Bg* mostly 1-10 cm/d, air capacity <3 vol%, no segregates)
Typischer Haftnassepseudogley:
Ah–Bg (<17% T[c], >50% U+ ffS)–*C* (>30 cm) — *SHn*

Toniger Haftnassepseudogley:
Ah–Bg (17-35% T, 50% U + ffS)–*C* (>30 cm) — *SHt*

Sandgrundiger Haftnassepseudogley: $\frac{Ah\text{–}Bv}{40\text{-}80\ cm}\text{–}\frac{IIC}{S}$ *SHs*

Braunerde-Haftnassepseudogley:
$\frac{Ah\text{–}Bv\text{–}Bg \text{ or } Ah\text{–}Bvg\text{–}Bg}{<40\ cm}$ *B-SH*

Parabraunerde-Haftnassepseudogley:
$\frac{Ah\text{–}Al\text{–}Bt\text{–}Bg \text{ or } Ah\text{–}A1g\text{–}Btg}{<40\ cm}$ *L-SH*

Gley-Haftnassepseudogley: $\frac{Ah\text{–}Bg\text{–}Go\text{–}\ (Gr)}{40\text{-}80\ cm}$ *G-SH*

1.10.3 Stagnogley (type)
Surface water soil with *Aeg* horizon
e.g. (wet bleached) = bleached like *g*, but without concretions
Typischer Stagnogley: $Aegh\text{–}\frac{Aeg}{>20\ cm}\ \text{–}\frac{Bg}{kf<1}\ (\text{–}Cg)\ \text{–}C$ *SSn*

Anmoorstagnogley: $\frac{HA\ (15\text{-}30\%\ org.\ subst.)}{>10\ cm}\ \text{–}Aeg\ \text{–}\frac{Bg}{kf<1}\ (\text{–}Cg)$ *SSa*

Moor (resp. Torf) stagnogley:
$\frac{H\ (>30\%\ org.\ subst.)}{0.2\text{-}30\ cm}\ \text{–}Aeg\text{–}\ (\ \frac{Bg}{kf<1}\ \text{–})\ C$ *SSh*

Gley-Stagnogley: $\frac{Ah\text{–}Aeg\text{–}Bg\ (kf<1)}{40\text{-}80\ cm}\ \text{–}G$ *G-SS*

2. Semiterrestrial soils (order)
Mineral soils influenced by groundwater (i.e., having a *G* horizon) in the upper 40 cm and/or periodically flooded unless dammed
G = mineral horizon with
1. (temporary) wetness from groundwater *and*
2. a) *Go*: oxidized (rusty spots >5% by area, especially on aggregate surfaces or in root channels) *or*
   b) *Gc*: calcic ($CaCO_3$>15% and >1.05·$CaCO_3$ of C or secondary lime >5% by volume) *or*
   c) *Gr*: reduced (1. wet >300d/a and rH≤19 and color N1-8 >95% by area or hue 5*Y*, 5*G*, or 5*B* and chroma <1.5, if *G* <2.5)

2.1 Auenboden (suborder)
Soils from holocene alluvial sediments (= *aC*) periodically (episodically) flooded with fresh water, without *G* horizon in the upper 80 cm

2
2.1.1 Rambla (Auenrohboden): $\frac{(A)\ \text{-}\ aC\ (\text{-}G)}{>80\ cm}$

Typische Rambla (Auensilicatrohboden): *aC*<2% $CaCO_3$ *AO*
Kalkrambla (Auencarbonatrohboden): *aC*≥2% $CaCO_3$ *AC*

2.1.2 Paternia (Auenregosol): $\frac{Ah\ \text{-}\ Ac\ (\text{-}G)}{>80\ cm}$, *aC*<2% $CaCO_3$ *AQ*

2.1.3 Kalkpaternia (Auenregorendzina): as *AQ*, *aC*>75% $CaCO_3$ *AR*
2.1.4 Auenpararendzina: as *AQ*, *aC* 2-75% $CaCO_3$ *AZ*
2.1.5 Borowina: as *AR*, but with dark Mull-*A* *ARh*
2.1.6 Tschernitza: as *AZ*, but with dark Mull-*A* >40 cm *AT*

2.1.7	Allochthoner brauner Auenboden: $\frac{Ah\text{ - }aC}{>80\text{ cm}}$ (a : brown colluvium) - (*G*)		
	Typische allochtone Vega: upper *aC* lime-free		*An*
	Allochthone Kalkvega : *aC* calcareous		*Ac*
2.1.8	Vega (Auenbraunerde: $\frac{Ah\text{-}Bv\ (\text{-}aC)\text{ - }(\text{-}G)}{>80\text{ cm}}$		*AB*
	Typische Vega : see AB		*ABn*
	Kalkvega : Bv with secondary lime		*Abk*
	Gley-Vega : $\frac{Ah\text{ - }(Bv\text{-})\ GoBv\text{ - }Go\text{ - }Gr}{>80\text{ cm}}$		*AG-AB*
2.1.9	Auenparabraunerde: $\frac{Ah\text{ - }Al\text{ - }Bt\ (\text{-}Bv)\text{ - }aC\text{ -}G}{>80\text{ cm}}$		*AL*
2.2	(Grund) gleye (suborder) Mineral soils of valleys and plains influenced by fresh groundwater in the upper 40 cm		
2.2.1	(Grund) gley	: *Ah* (<40 cm or *Aoh*) - *Go* (-*Gr*)	*G*
	Typischer Gley	: *Ah - Go - Gr*	*Gn*
	Oxigley	: *Ah - Go*	*Go*
	Raseneisensteingley	: *Ah - Gmo - Gr*	*Ge*
	Humusgley	: as *Gn, Ah* 8-15% org. subst.	*Gh*
	Kalkhaltiger Gley	: *Ah - Gco - Gr*	*Gc*
	Kalkgley	: *Ach - Goc - Gr*	*Gk*
	Regosol-Gley	: $\frac{Ah\text{ - }C}{<40\text{ cm}}$ *-Go - Gr*	*Q-G*
	Pelo (sol-) gley	: $\frac{Ah\text{-}Ba\ (\text{resp. Ca})\text{ - }Go\text{ - }Gr}{<40\text{ cm}}$	*D-G*
	(a: clay >45%, temporarily cracked)		
	Braunerde-Gley	: $\frac{Ah\text{ - }Bv\text{ - }Go\text{ - }Gr}{<40\text{ cm}}$	*B-G*
	Parabraunerde-Gley: $\frac{Ah\text{-}Al\text{ - }(Bt)\text{ - }BtGo\text{ - }(Go)\text{ - }Gr}{<40\text{ cm}}$		*L-G*
	Podsol-Gley	: (0-) $\frac{Aeh\text{ - }Ae\ (\text{-}\ Bh)\text{ - }BhG\text{ - }Gr}{<40\text{ cm}}$	*P-G*
	Pseudogley-Gley	: $\frac{Ah\text{ - }Ag\ (\text{-}Bg)\text{ - }BgGo\text{-}Gr}{<40\text{ cm}}$	*S-G*
	Plaggenesch-Gley	: $\frac{Ah\text{- }pD\text{-}pDGo\text{ - }(Go\text{-})Gr}{<40\text{ cm}}$	*E-G*
	pD = Plaggen layer		
2.2.2	Nassgley	: *Aoh-Gr*	*G-N*
2.2.3	Anmoorgley	: *HAo-Gr*	*GA*
	Typischer Anmoorgley: lime-free		*GAn*
	Kalkhaltiger Anmoorgley: calcareous (<10%) throughout the profile		*GAc*
	Kalkanmoorgley: calcareous (>10%) throughout the profile, with secondary lime		*GAk*
2.2.4	Moorgley	: $\frac{H}{<30\text{ cm}}$ *- Gr*	*GH*
2.3	Quellengley Gleys near springs or on slopes (>9%)		*Q*
2.3.1	Quellengley	: *Ah - Go - G* (o) *r*	*QG*

	Typischer Quellengley : $\frac{Ah - Go - G\ (o)r}{40\text{-}80\ cm}$		*QGn*
	Oxiquellengley	: *Ah - Go*	*QGo*
	Kalkhaltiger Quellengley	: *Ah - G (c)o-G(c)r*	*Qgc*
	Kalkquellengley	: *Ach - Goc - Gr*	*QGk*
2.3.2	Anmoorquellengley	: $\frac{HA}{10\text{-}40\ cm}$ *- Gr*	*QA*
2.3.3	Moorquellengley	: $\frac{H}{<30\ cm}$ *- Gr*	*QH*
2.4	Marschen Soils from tidal sediments (z = high salinity = EC of saturation extract <4 dS/m)		
2.4.1	Salzmarsch	: *zAoh - (zGor-)-zGr*	*MZ*
2.4.2	Kalkmarsch	: $\frac{Ah - Go - (z)\ Gr}{\text{calcareous}}$	*MC*
	Typische Kalkmarsch	: GWL >80 cm	*MCn*
	Nasse Kalkmarsch	: GWL <80 cm	*MCa*
	Unreife Kalkmarsch	: *Aoh- (z) Gro- (z) Gr*	*MCg*
	Staunasse Kalkmarsch	: *Ah - (Ag-)* $\frac{BgGo}{kf<1}$ *- (z)Gr*	*MCs*
2.4.3	Kleimarsch : $\frac{Ah - Go}{>30\ cm\ lime\text{-}free}$ *- Gr*		*Mn*
	Subtypes as Kalkmarsch		
2.4.4	Knickmarsch : $\frac{Ah - Ag - Bg\ (kf<1) - (Go) - Gr}{>70\ cm,\ lime\text{-}free}$		*MK*
3.	Subhydrical soils (order) Soils at the bottom of lakes or seas with epipedon containing organic substances >1%		*J*
3.1	Protopedon (Unterwasserrohboden) : *(F) - G* Typisches Protopedon Marines Protopedon		*JP*
3.2	Gyttja : *Fh* (olive, pH≥7, Eh>200 mV) *- G*		*JG*
3.3	Sapropel : *Fr* (black, pH≥7, Eh<200 mV) *- Gr* Typisches Sapropel Marines Sapropel (Schlickwatt)		*JS*
3.4	Dy	: *Ff* (black, pH≥6, Eh<200 mV) *- Gr*	*JD*
4.	Peat soils (order) Soils with *H* horizon (organic substances >30% and wet >30 subsequent days unless drained) >30 cm, n = phragmites-carex-peat, *u* = containing remnants of *Betula pubescens, h* = sphagnum-eriophorum-peat		*H*
4.1	Niedermoor	: $\frac{nH}{>30\ cm}$ *- (F-)Gr*	*HN*
	Typisches Niedermoor	: *H* : lime-free, V >30%	*HNn*
	Kalkhaltiges Niedermoor	: *H* calcareous	*HNc*
	Saures Niedermoor	: nH: *V* <30% and/or $\frac{hH - (uH)\text{-}nH\text{-}Gr}{<30\ cm}$	*HNs*
4.2	Ubergangsmoor	: *uH - nH* - (F-)*Gr*	*HU*
4.3	Hochmoor	: *hH- ... Gr*	*HH*
	Typisches Hochmoor	: *hH - (uH) - nH - (F) - Gr*	*HHn*
	Wurzelechtes Hochmoor	: *hH* - f*Ah* . . .	*HHw*
	Subdivision according to underlying mineral soils (Podsol, Podsol-Gley, Stagnogley etc.)		

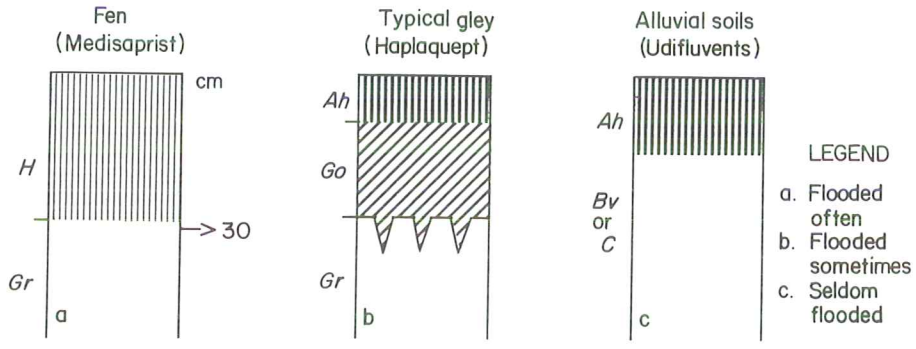
[a] Symbols used in soil maps. [b] In perhumid climate or on slopes (>9%) <10 cm/d. [c] T = clay, U = silt, S = sand, (f) f = (very) fine.

Contrary to this, in typical surface water soils the aggregate surfaces of the clayey, denser subsoil (Bg) impeding the drainage are bleached and depleted of Fe and Mn oxides, whereas the cores are enriched with brown Fe and blackish Mn oxides (or with orange lepidocrocite in very clayey, lime-free, slightly acid soils). Thus, the profile is "marbled" by small white vertical streaks side by side with broader rusty-brown ones. Horizontal cuts through these horizons reveal a whitish polygonal pattern (that may stem from frost cracking under periglacial conditions) increasing in width but decreasing in degree of bleaching with depth. The matrix of the less clayey and less dense topsoil (Ag), temporarily saturated with water, is brownish gray. Mainly right above the Bg horizon, Fe and Mn are concentrated in concretions differing considerably in size, with an onion-shaped structure occurring in homogeneously textured material such as loess. Frequently, black Mn oxides predominate at the center and rusty-brown Fe oxides nearer the surface. The longer the wetness lasts, the more this horizon becomes gray and finally white. Thus, the distribution pattern of Fe/Mn oxides in these soils is "introvertly" oriented away from the ped and the soil surface, from where the reducing organic compounds come.

In the following sections, we shall describe variations in the morphology of groundwater and surface water soils and finally some interference between both types.

DIFFERENTIATION OF GROUNDWATER SOILS

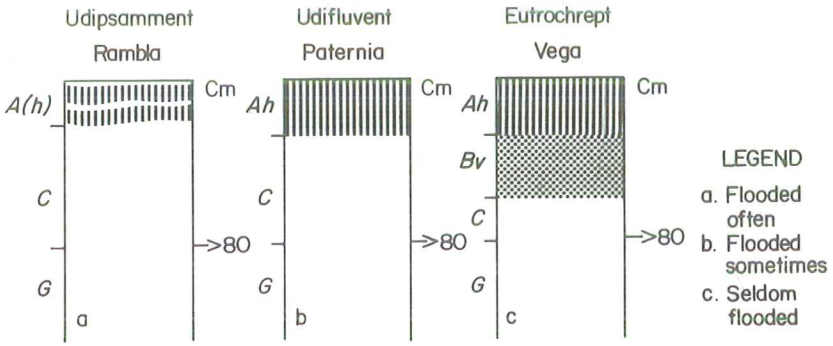
Figure 2 demonstrates the range of groundwater soils. Permanently high and stagnant groundwater causes the development of a fen (Niedermoor). The less the groundwater fluctuates during the year, the poorer the soil is in nutrients, and the cooler its peaty H horizon is, the less it is humified. On the other hand, soils of



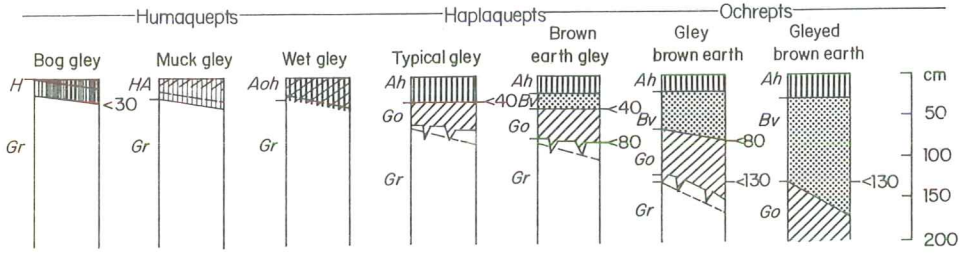
2. Archetypes of groundwater soils.

alluvial plains with only seasonal flooding and with groundwater fluctuating frequently and moving quickly through coarse pores may essentially lack redoximorphic features except for some rusty spots. These alluvial soils (Auenboeden, Fig. 3) differ from dryland soils only in that they are periodically wet and are more or less finely stratified (like marsh soils). The Rambla has only an ochric epipedon whereas the Paternia and the Vega may be umbric or mollic; moreover, the latter has a cambic horizon.

Gleys with an appreciable content of clay or bases and, at most, slowly moving groundwater are more or less redoximorphic, depending mainly on the mean groundwater level (GWL) and its seasonal variation. At a mean GWL of 40-80 cm typical groundwater gleys with normal Go and Gr horizons are developed (Fig. 2b). The distance between the bottom of the Go horizon and the mean GWL increases with the clay content and the bulk density, whereas the thickness of the Go increases with fluctuations of the GWL. This amplitude may vary between <20 cm in closed depressions and >100 cm in alluvial plains. At a mean GWL of less than 40 cm, the Go coincides with the humus horizon (Fig. 4; 3) and Fe oxide precipitates around root channels; also, small, blackish-brown concretions can be seen in the topsoil. According to the organic matter content of the epipedon



3. Alluvial soils (Auenböden).

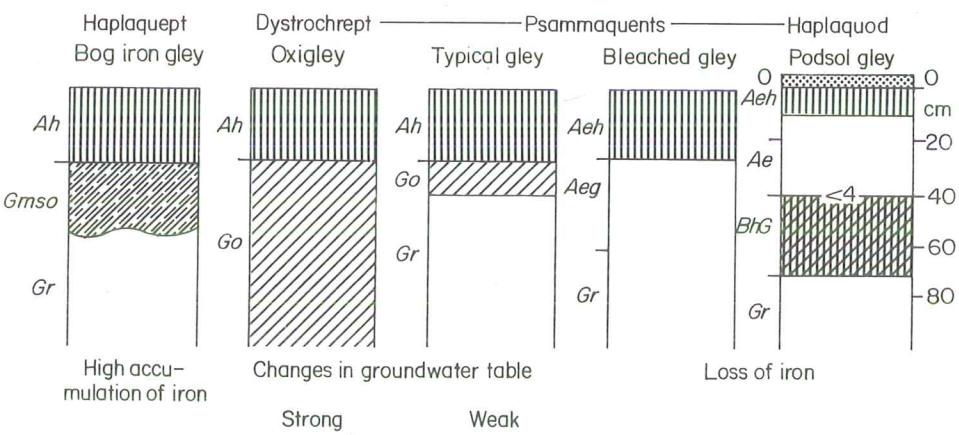


4. Gleys (loamy and/or eutrophic) with groundwater table (---) and with the maximum depth of diagnostic horizons (in cm).

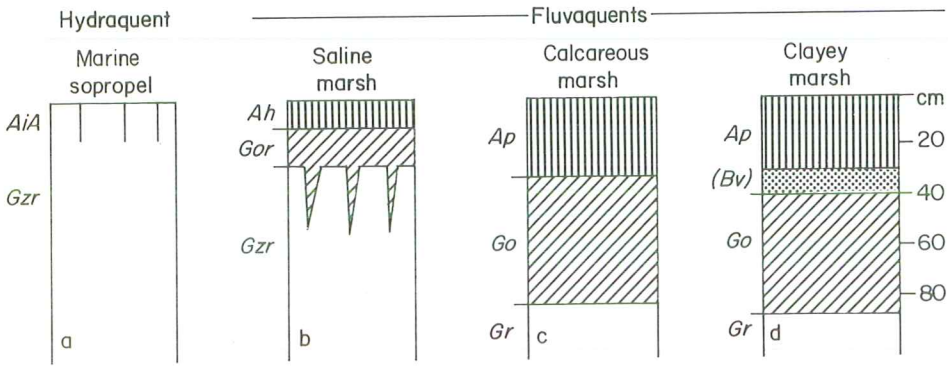
(>2 cm), the following subtypes are recognized: <15% = wet gley (Nassgley), 15-30% = muck gley (Anmoorgley), and >30% = bog gley (Moorgley). On the other hand, when the mean GWL is more than 80 cm, a mostly cambic or an argillic horizon is developed between the A and Go horizons, which is less redoximorphic with increasing depth of occurrence.

When the clay contents and the amplitudes of the GWL are low (Fig. 5), the Go is often only 10 cm thick and sharply contrasts with the whitish Gr horizon. The interstitial pores in the Go are filled with reddish-brown Fe oxides, often darker toward the top because of an increasing Mn content (5). In sandy gleys with a strongly fluctuating GWL, the Go is poor in Fe and Mn oxides but very thick. In the extreme case there is no Gr at all. These oxigleys are frequently anthropogenic because of a continuous lowering of the GWL. Locally, Fe oxides can be accumulated in large amounts and then can cement the matrix in the bog iron gley (Raseneisengley). Such soils are rather typical for broad valleys with fluvioglacial sands in northwest Germany, often occurring in a narrow fringe accompanying the water courses. There Fe suppliers are the Podzols dominating the adjacent uplands as well as the bleached Podzol gleys in intermediate positions that are nearly devoid of Fe oxides.

The sediments near the North Sea are more or less finely stratified, saline, calcareous, and sulfidic -- the clayey more than the sandy ones. Where this material is aerated only during low tide, the black of the Fe sulfides is still the predominant color, and only the upper few millimetres may be olive because of Fe(II/III) oxides or a lawn of algae; the walls of worm channels may be covered by rusty Fe oxides in the marine Sapropel (Schlickwatt, Fig. 6a). Beyond this amphibic fringe begins the area of the marshes, which



5. Gleys (sandy and/or dystric) with different redoximorphism.

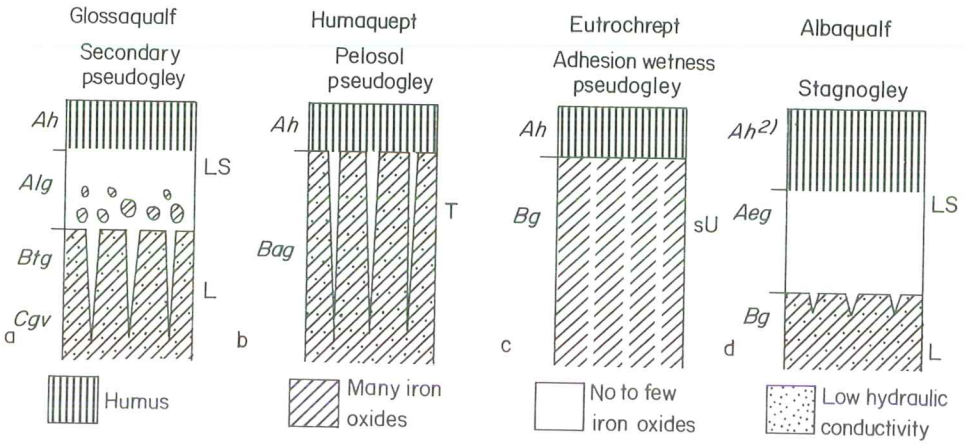


6. Soils from marine sediments (from a to c lower groundwater table, from b to c loss of salts and carbonates, and from a to d increase in bulk density).

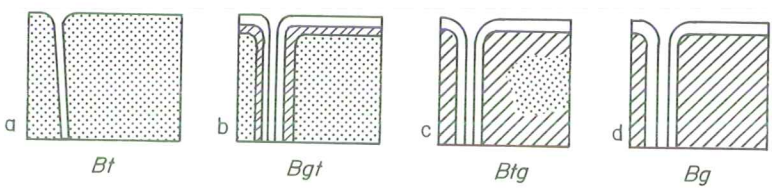
in the German system represent a suborder of the groundwater soils. In the Gor of the saline marsh (Salzmarsch) only the material near the sometimes deep cracks and in worm channels is rusty. Here the cores of the aggregates are olive, which applies at most to their surfaces in the Gr. Nearly all other soils in this region are protected against flooding by dikes and are drained by trenches, which promotes desalinization -- leaving the calcareous marsh (Kalkmarsch) -- decalcification -- leaving the clayey marsh (Kleimarsch) -- and oxidation. The distribution pattern of Fe and Mn oxides is related to the strata in the coarser sediments and to the cracks in the others.

DIFFERENTIATION OF SURFACE WATER SOILS

Surface water soils also differ considerably in their morphology (Fig. 7). The typical pseudogley is texture differentiated by stratification or lessivage, in which case it is named secondary (Fig. 7a). In weakly developed Bg horizons the aggregate surfaces show only a thin bleached seam followed by a rusty one, whereas their cores differ from those of normal argillic or cambic horizons (Fig. 8a) merely by the appearance of some small blackish-brown Fe/Mn concretions (Fig 8b). Increasing water stagnation due to higher bulk density or clay content, cooler or moister climate, or intake by interflow causes an extension of the bleached seam and the rusty spots (Fig. 8c), and finally the microstructure shows no remnant of the argillic or cambic horizon (Fig 8d). Under an annual precipitation of 700-800 mm, the typical Bg has a saturated hydraulic conductivity <1 cm/d (in a perhumid climate or on a slope even <10 cm/d may be sufficiently low). With a given moisture regime, the redoximorphic color pattern also depends on the substrate, e.g., goethitic loess



7. Archetypes of surface water gleys (LS = loamy sand, L = loam, T = clay, sU = sandy silt).

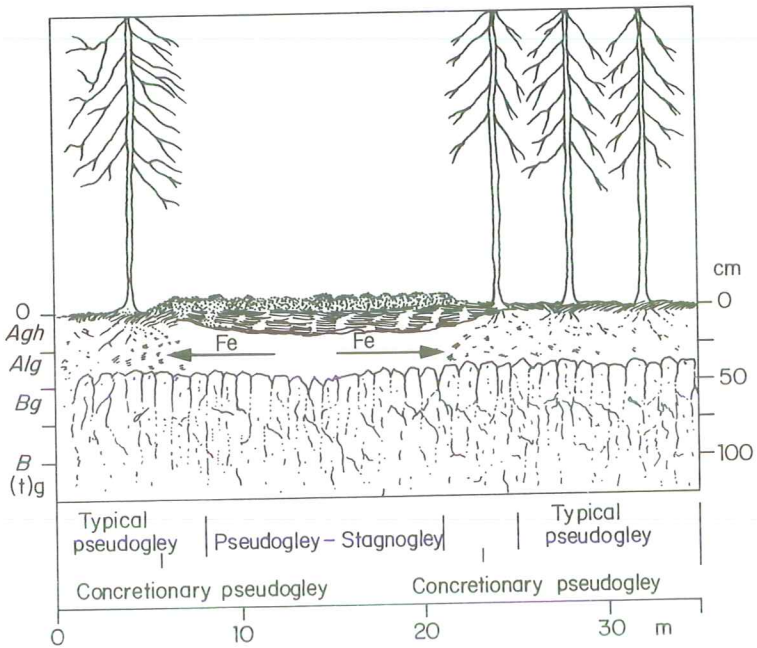


8. B horizons of Alfisols with weak (Bt) to strong (Bg) surface waterlogging.

shows up much better than hematitic sandstone (10). Weakly developed Alg horizons of secondary pseudogleys are pale at first because of the clay eluviation, but with increasing O_2 deficiency bleaching follows under formation of concretions. In the typical pseudogley, Fe is translocated only within the horizons; the Fe_d-clay ratio remains constant throughout the profile. But there are also pseudogleys poor or rich in concretions with corresponding differences in this ratio. This can be caused by lateral translocations because of local differences in wetness (Fig. 9).

The homogeneously clayey pelosol pseudogley (Fig. 7b) lacks a concretionary Ag; at most its humus horizon contains small brown concretions. In the Bag the aggregates become larger (from blocky to prismatic) and more redoximorphic with depth. Most pelosol pseudogleys, however, have a coarser topsoil (e.g., by admixture of loess), which causes the formation of a thin Ag horizon.

Adhesion wetness pseudogleys (Haftnaessepseudogleys, Fig. 7c) are mottled rather monotonously. They are developed in an oceanic climate from fine sandy-silty, coherent material. The saturated hydraulic conductivity is 10-40 cm/d. But in these soils, almost all pores are capillaries <60 µm, thus allowing nearly no aeration at field capacity. Consequently, these



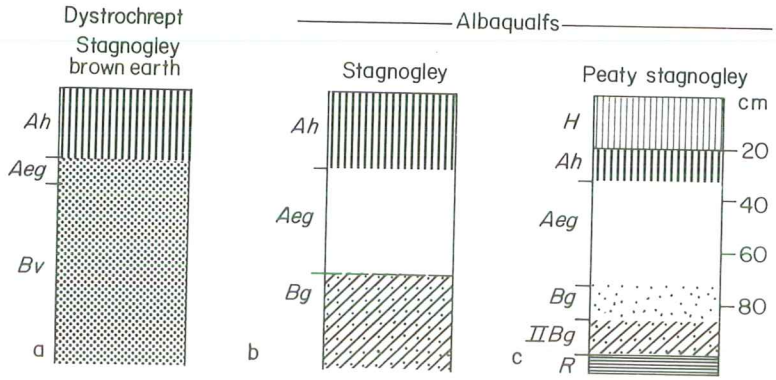
9. Pseudogleys (Aqualfs), partly with lateral translocation of iron in the topsoil (2).

soils show rusty and bleached spots, the latter especially near root channels.

Stanogleys (Fig. 7d) have a clayey, "marbled" Bg as described earlier, but their topsoil is devoid of concretions strongly bleached, and therefore named Aeg. In a cool, humid mountain climate the A horizons are wet for a long time and never sufficiently dry to allow concretions to be formed or preserved. Even on nearly level surfaces the excess water moves laterally, causing a translocation of Fe and Mn downslope, where they are reprecipitated (8). Where the wet period is shorter (watershed or slope position, water conductivity less different between topsoil and subsoil), the Aeg is only thin (Fig. 10a), but where the saturation is nearly permanent, a histic H is developed in addition to a thick Aeg (Fig. 10c).

COMBINATION OF GROUNDWATER AND SURFACE WATER PHENOMENA

In some wetland soils surface water and groundwater phenomena are combined. This combination applies to the stratified gley-pseudogleys and the pseudogley-gleys, which have an "introverted" distribution pattern of Fe oxides in their topsoil but an "extroverted" one in the subsoil influenced by groundwater. In the marsh region, such soils with a dense clayey layer (Knick) and bleached surfaces of the blocky aggregates are

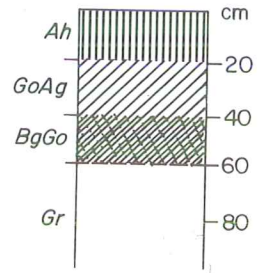


10. Surfacewater gleying under cool and humid conditions with weak to strong lateral leaching of iron.

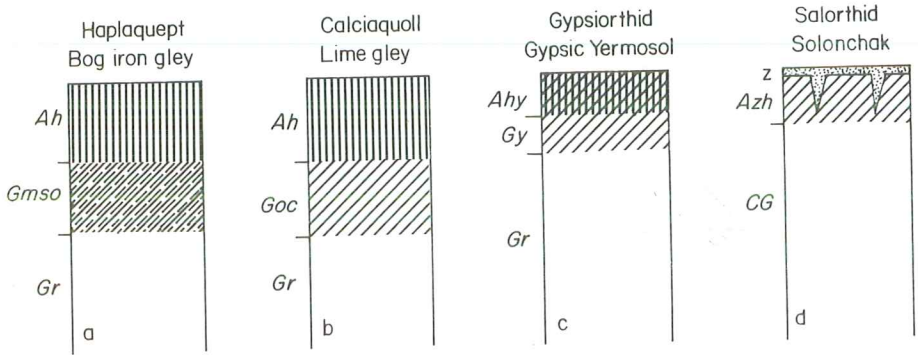
classified as Knickmarsh (Fig. 11). In many slope soils surface water and groundwater phenomena occur side by side since the interflowing water sometimes moves upward and sometimes downward. This makes it difficult to distinguish, by morphology alone, between spring gley (Quellgley or Hanggley) and slope gley/pseudogley (Hangpseudogley).

REDOXIMORPHIC, CALCIMORPHIC, GYPSIMORPHIC, AND HALOMORPHIC SOILS

Wetland soils may show other hydromorphic features together with, or instead of, the redoximorphic ones. In groundwater soils under humid conditions, this depends mainly on the parent material and the soil cover of the catchment area. Old moraine landscapes with Spodosols are characterized by bog iron gley (Fig. 12a), the young ones with Alfisols by lime gley (sometimes with a strong meadow lime accumulation in the Goc, called Wiesenkalk Fig. 12b). In surface water soils under semihumid conditions, lime is often concen-



11. Pseudogley - gley or Knickmarsh soil with surface water and groundwater gleying.



12. Groundwater soils under different climate conditions with strong accumulation of iron (a), carbonates (b), gypsum (c), or salts (d).

trated in coarser concretions, whereas in permeable soils, the secondary lime is finely distributed. Under drier conditions the accumulation of lime is frequently replaced by a concentration of gypsum or even of salts (Fig 12c, d,). Crusts, more or less connected with a takyric structure, are formed where the capillary fringe reaches the surface, whereas atmogenic salts are never concentrated there. In the real desert, redoximorphic features are rare.

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MORPHOLOGICAL CHARACTERISTICS OF WET SOILS

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The best micromorphological indicator of hydromorphism is the presence of typic sesquioxidic features. Manganese segregations (mainly coatings and hypocoatings) dominate in slightly hydromorphic materials. With increasing hydromorphism, Fe hydroxide segregations appear in the groundmass (as diffuse nodules and hypocoatings) and low chromas in the peds. In strongly hydromorphic materials, low chromas dominate and Fe- hypocoatings and quasicoatings may occur around the larger voids. In groundwater gleys the groundmass has a low chroma, and Fe- hypocoatings and quasicoatings occur along macropores; in surface water gleys, imperative nodules are more abundant. According to the position in the profile and the pedogenetic evolution of the soil material, specific features may develop.

Wet soils cover a relatively important area of the world's land mass and may be found in practically every climatic zone. They may point to the presence of a high groundwater table or to an impermeable layer close to the surface, or they may result from natural or artificial flooding of the soil during part of the year. According to the dominant pedogenetic processes active in the area and the degree of evolution of the soil material, different morphological expressions of this "wetness" may be expected. Some special developments are found, for instance, in acid-sulfate soils, peaty soils, soils situated in sabkhas, etc.

Although the micromorphology of many hydromorphic profiles has been described in the literature, few systematic studies are available. Only in a few papers has an attempt been made to compare, for instance, hydromorphic and well-drained soils, or different

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degrees of hydromorphism, or the impact of hydromorphism on different types of parent materials. Most of the publications suffer, moreover, from a lack of precision in the micromorphological terminology used or in the characterization of the profiles studied, or in both.

One of the pioneer papers on this subject is that of Bluemel (4) discussing the different forms of Fe segregations in groundwater and surface water gleys. Another important contribution is that of Veneman et al (24) on the evolution of sesquioxides in a soil sequence with increasing duration of water saturation.

Most papers deal with the characteristics of hydromorphic soils in temperate climates, and therefore often with those of hydromorphic Alfisols or Spodosols. The real expression of actual hydromorphism in the former is frequently troubled by the presence of paleofeatures, many of which seem polycyclic.

The micromorphological terminology used in this paper is that proposed by Bullock et al in the ISSS Handbook for soil thin section description (8).

MICROMORPHOLOGICAL EXPRESSION OF DIFFERENT DEGREES OF SATURATION

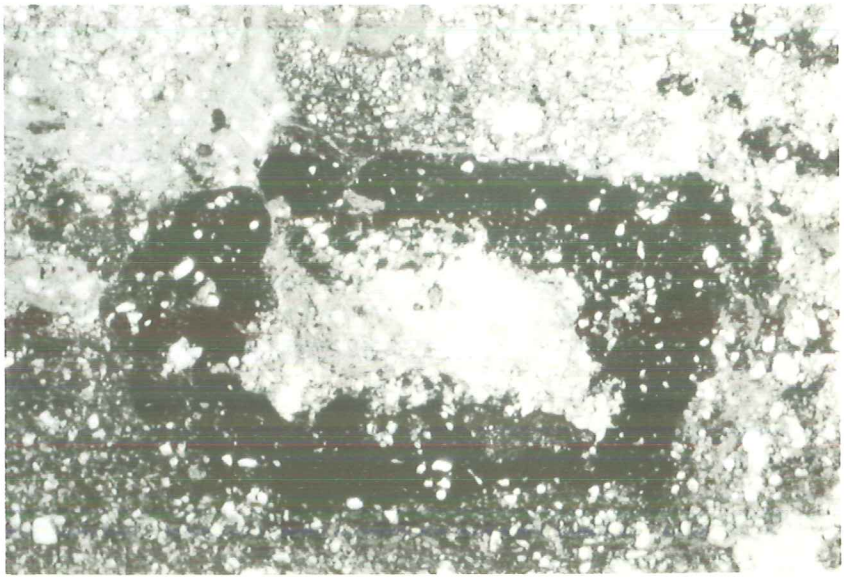
Because many authors do not differentiate between groundwater and surface water gley soils, a general description of the material under increasing hydromorphic conditions is in order. One of the key papers on this subject is that of Veneman et al (24), describing systematically the change in microfabrics of the sesquioxides in a soil sequence with increasing hydromorphic characteristics.

Weak hydromorphism

Soil materials that are subject only from time to time to short periods of saturation show little or no mobility of the Fe. Therefore the high chroma of the matrix is preserved. Manganese is more readily reduced than Fe and can be translocated to the ped surfaces, where it is precipitated as Mn coatings and hypocoatings (Fig. 1). Some Mn nodules may be formed, too. Experimental work on gleying by Vepraskas and Bouma (25) proved that in unsaturated soil cores, the color of the material remained unchanged and coatings of Mn developed on ped surfaces, corroborating the field observations.

Moderate hydromorphism

Soil materials saturated during several consecutive days show a clear mobility of the Fe present. Only the largest pores are filled most of the time with air, and



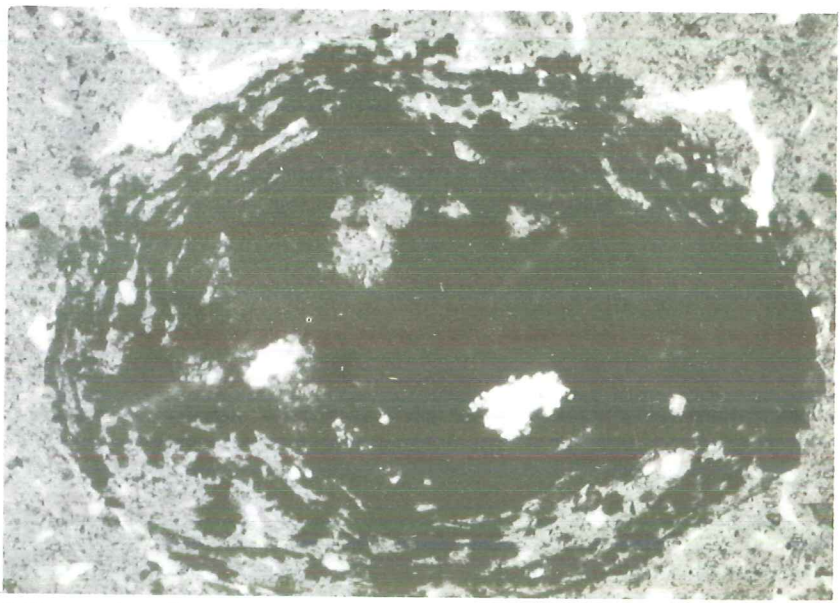
1. Coatings and hypocoatings of manganese on pores and peds. Cg of Tropaqualf, Philippines. Plain light, 100 x.

the ped interior remains practically constantly wet and is the seat of reduction of Fe and Mn compounds. That gives rise to low chromas inside the peds as well as some intrapedal nodules. Most of the Fe, however, moves from inside the peds to their surfaces and is precipitated there as hypocoatings on planes and channels as a result of its oxidation (Fig. 2). In somewhat wetter conditions, water may move through the voids, depositing coatings of Fe oxyhydrates on the walls of voids. Manganese, which is more readily reduced than Fe, is generally leached down the profile or may be present as black diffuse nodules (Fig. 3).

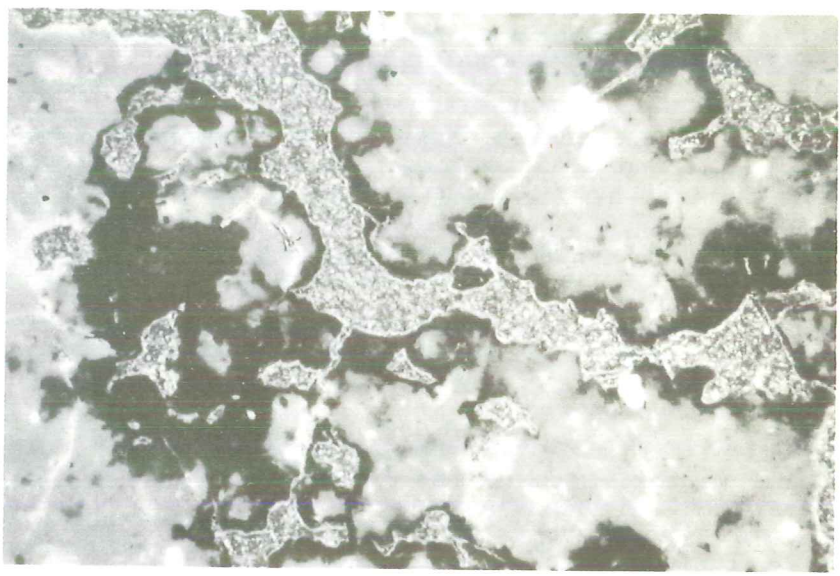
Strong hydromorphism

When the soil material remains completely wet during several months, much of the Fe and Mn is removed from the profile. Inside the peds, low chromas are therefore observed. Around voids hypocoatings of Fe oxyhydrates may be formed, which can be bleached subsequently near the pore space, transforming them to quasicoatings (Fig. 4). In the case of a very deficient vertical permeability, Fe and Mn oxyhydrates may be deposited as coatings around voids.

Because of the long anaerobic conditions, many plant remains are preserved in the soil material. According to Dobrovolsky et al (9), constantly wet soil horizons usually lack the well-developed compact ferruginous segregations with distinct boundaries,



2. Hypocoatings of brown iron-oxyhydrates along channel. Ap_2 of Pellustert, Philippines. Plain light, 100 x.



3. Irregular opaque, impregnative nodule of manganese (hydro)oxides, formed in situ, ACgb of Pellustert, Philippines. Plain light, 100 x.

which testify to the periodic character of soil wetting, and they are rather found in the zone where reduction and oxidation regimes alternate most frequently.

Experiments by Vepraskas and Bouma (25) showed that in saturated soil cores, zones of Fe depletion up



4. Quasicoating of iron-oxyhydrates around channel. Note the bleached zone just adjoining the channel walls. BAg of Tropaquept, Philippines. Plain light, 100 x.

to 2 mm developed around voids, surrounded in turn by quasicoatings of Mn. In the ped interior, fine prominent Mn mottles developed, as well as fine faint Fe nodules. Only the beginning of the gley formation is illustrated here, as the time was relatively short. Manganese features are therefore better expressed than Fe features.

A 2-year gleying experiment by Narokova and Yarilova (15) on different types of parent material showed no changes in the composition of the material but showed an increase in compaction and a general bleaching. The micromass gained mobility, as shown by the presence of clay accumulation and alluviation phenomena. Dark-brown isotropic coatings covered the walls of the pores. A fragmentation of the coarse grains, as well as a decoloration of ferruginous minerals along their borders, was observed.

If sufficient clay is present, the gley horizons exhibit a porphyric c/f-related distribution pattern; in other cases a chitonic or gefuric one is most common. Most authors agree that the reduced zones of the gley soils have a well-developed strial b-fabric, even when the overlying soil material and the brown mottles show only a speckled b-fabric. This higher mobility of the clay is attributed to the absence of the stabilizing Fe oxyhydrates and eventually the addition of Mg or Na ions (12). Therefore, clay coatings are easily destroyed in reduced zones, as stated, among others, by Begon (3) about a hydromorphic degraded leached soil in France. He also observed the

presence of birefringent streaks in the reduced zone at its contact with the brownish zone, indicating stresses in this situation.

Extremely developed gley soils, especially those subject to flooding, may contain high amounts of diatomic algae (9, 21).

Aggregation is very weak or is absent in most gley horizons.

Evolution of features in the profile

In most cases a characteristic sequence of Fe or Mn features or both may be observed throughout the profile; in the deeper layers hypocoatings and diffuse typic nodules prevail, which are replaced by clear ferric nodules in the overlying layer. Higher in the profile, the nodules become more distinct and are sometimes relatively hard and consistent, as can be deduced from the development of granostriated b-fabrics around them. Similar observations have been made by many authors, e.g., Rudeforth (18) and Slager et al (19).

The fabric of the surface horizons is determined essentially by the humus type present (14). Matinjan (13) notes that, in the sequence he investigated, the A1 becomes darker with increasing hydromorphism.

One studying the micromorphology of hydromorphic soils should realize that the morphological expression of gleyification is also a function of the availability of Fe and Mn compounds from weathering (1).

Scanning electron microscope studies showed that in weakly or moderately gleyed soils the surfaces of the grains and pores are covered with ferruginous coatings. Under more pronounced gleyification, these coatings are destroyed and the porewalls become bare (9). The peripheral zone of the aggregates and voids acquires a loose arrangement. According to several authors, the internal fabric of the brown zones (with Fe segregation) is much denser than that of the grayish zone.

GROUNDWATER VERSUS SURFACE WATER GLEY

Soils with groundwater gley

The morphology of the gley horizons of these soils is characterized by a dominance of reduction features over Fe segregations. The groundmass has a relatively low chroma compared to similar but well-drained materials. Oxidation occurs only along macropores such as root and other channels and eventually along planes (4, 9), giving rise to the formation of hypocoatings and quasicoatings of brownish isotropic Fe oxyhydrates, frequently still associated with decaying plant roots,

illustrating that these features were only recently formed and may disappear later as a result of reduction. Matinjan (13) also reports a ferruginization of plant residues in this zone.

According to Bluemel (4) typic impregnative nodules of the same brownish material with diffuse boundaries occur on slopes.

In the upper part of the gleyified horizon, quasicoatings and hypocoatings tend to be replaced by diffuse, and later by sharp typic (undifferentiated) nodules as a result of differential movements in the soil (because of changes in moisture content) that fragment the coatings and smooth their fragments. Compact and sharp Fe segregations testify to the periodical character of the moistening.

Eswaran (10) showed that, for a sequence of wet Alfisols in Belgium, the total volume of clay coatings increased with a greater amplitude in the groundwater fluctuations.

Surface water gley

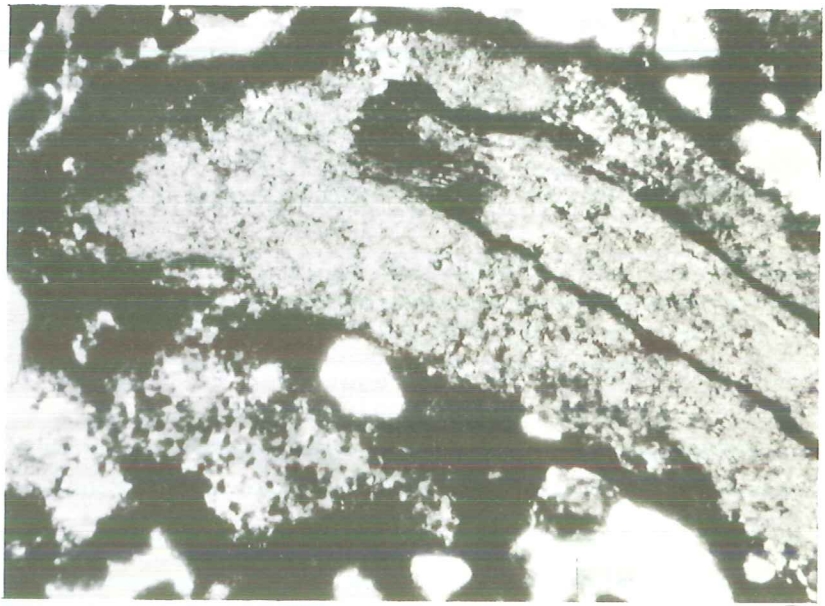
Reduction is less important in surface water gley than in groundwater gley. Reprecipitation of the mobilized Fe depends upon the physicochemical conditions in the material. Thomasson and Bullock (23) reported that in a calcareous soil, reprecipitation may be complete after 3 days, whereas in heavy clays the process may take more than 30 days. In the case of a slow reprecipitation, the Fe may be completely lost in the drainage water. Slow reprecipitation also favors the formation of a coarse pattern of mottling, whereas fast reprecipitation tends to result in a fine, diffuse mottling.

In general, one may state that Fe oxyhydrate hypocoatings and quasicoatings are less important in surface water gleys than in groundwater gleys, as reported by Bluemel (4).

Most of the Fe segregations will appear as undifferentiated nodules (Fig. 5), less frequently as concentric nodules.

In the upper horizons of surface water gley soils, the nodules may be diffuse or sharp, depending upon the degree of gleying; a low chroma of the matrix is generally associated with sharp-bounded nodules. As these are frequently surrounded by a granostriated b-fabric, one may deduce that they are no longer active. Diffuse nodules and rare hypocoatings indicate a more active gleyification (18, 13). According to the latter author, a maximum of nodules is found at the bottom of the A2 horizon.

Fine, dark-colored spherical Fe-Mn nodules, often with a concentric fabric, are typic for the eluvial and illuvial horizons of weakly gleyified soils, whereas those of moderately or strongly gleyified soils contain



5. Irregular (left) and rounded (right) impregnative iron-manganese nodule. ACgb of Pellustert, Philippines. Plain light, 100 x.

less Mn, therefore have a more rusty color, and do not show a concentric fabric (27).

The gley horizon generally has a compact gray matrix with undifferentiated Fe nodules. In very wet conditions large, dark-brown nodules occur in a light-colored ped, whereas small, irregular nodules seem to occur in less wet soils (4). Along large channels reduction is prevalent, but smaller channels may be surrounded by brownish hypocoatings. Striated b-fabrics are strongly developed in the grayish zone and better expressed than in the upper horizons. In the mottles only weakly developed b-fabrics occur, such as speckled or undifferentiated, because of inhibiting sesquioxides (23). The higher stability of the Fe-impregnated zones is also shown by the better preservation of illuviation coatings. Rudeforth (18) notes that besides compactness Fe and clay coatings are the most persistent pedofeatures recognized in surface water gley subsoils. This is especially true when the subsoil is a fossil gley (e.g., 16).

SOME SPECIAL CASES OF HYDROMORPHISM

Hydromorphic Spodosols

The drainage characteristics of Spodosols partly determine their genetic evolution. Therefore, it is evident that their micromorphological characteristics are also influenced by hydromorphic conditions, e.g.,

the presence of monomorphic (in wet conditions) or polymorphic (in dry conditions) organic matter (17). Other examples were given recently by Barratt (1). A further discussion of this problem is beyond the scope of this paper.

Hydromorphic tropical soils

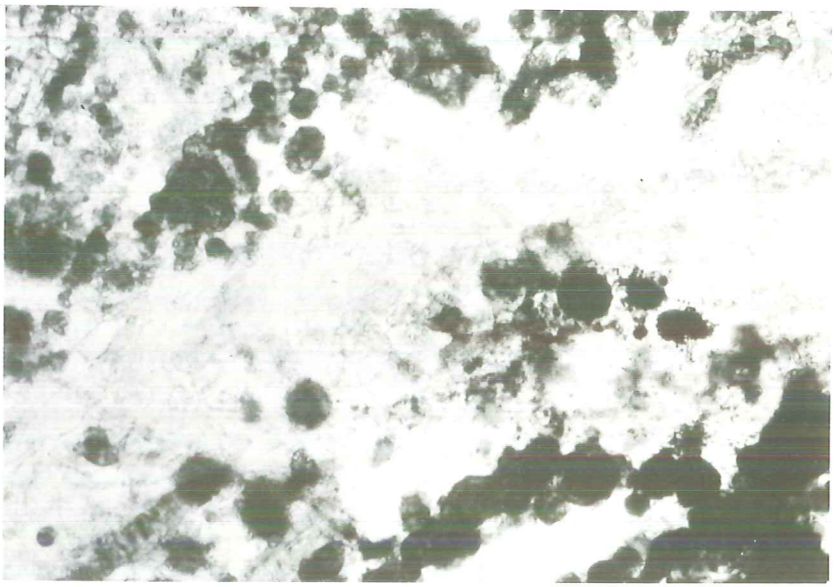
Little systematic information is available on micromorphological characteristics of hydromorphic soils in the humid tropics. Beaudou (2) describes the formation of compound clay coatings in the hydromorphic horizons of soils from central Africa. This process is attended by the formation of more or less square microaggregates with rounded edges, which change the original speckled b-fabric into a cross-striated one. In the upper layers, the b-fabric is speckled to weakly porostriated.

Seasonally flooded soils

Brammer (5) reports the presence of relatively thick (up to 0.5-mm) coatings of coarse clay in young soils that are naturally flooded during part of the year. These coatings form quite rapidly and generally have the same color and mineralogy as the topsoil. The fact that they are often banded points to successive flows. They are probably formed as a result of the reduction of the Fe compounds in the surface layers, which would provoke a dispersion of the fine material. These coatings are subject to a quick degradation to silty coatings. This is already visible in soils younger than 2,000 years.

NEW FORMATIONS AND TRANSFORMATIONS OF MINERALS IN HYDROMORPHIC SOILS

Strongly hydromorphic soils saturated with Fe-rich groundwater (more than 20 mg/litre, according to Zaidelman [27]) are especially rich in newly formed Fe minerals. In the upper layer, where an alteration of oxidizing and reducing conditions occurs, large zones of goethite crystallizations may be observed. Apart from cryptocrystalline, mostly isotropic, reddish-brown zones, a typic habit may appear: globular coatings consisting of radially arranged goethite needles or fibers apparently a few tens of microns long (11, 21). In the deeper layers, where reducing conditions prevail, minerals such as vivianite, siderite (Fig. 6), and pyrite may be found. These three minerals are frequently associated with decaying plant fragments, e.g., siderite around root channels and vivianite inside them. A more detailed analysis is given by Stoops (21).



6. Channel infilling of siderite grains with radial structure, surrounded by reddish-brown hypocoating of ironhydroxide. Bgl of Tropaqualf, Philippines. Plain light, 100 x.

Lepidocrocite has been identified by X-ray diffraction in the rusty zones of several hydromorphic soils. Because of the small size of these minerals, their micromorphological descriptions have not yet been reported.

In hydromorphic soils with somewhat saline groundwater, formation of barite as nests of thin prismatic minerals has been reported (22, 20). In arid and semiarid soils with a saline groundwater table near the surface, quite a number of new SO_4^-, CO_3^-, and Cl^- formations have been observed. Formation of new minerals such as pyrite, jarosite, and gypsum occurs in acid sulfate soils.

Brinkman (6) describes the destruction of phyllosilicates in hydromorphic soils. In a later publication (7) he illustrates micromorphologically the decomposition of clay coatings by ferrolysis in hydromorphic soils: birefringent clay coatings are altered to isotropic, grainy coatings with a bright opalescent reflection in incident light, probably as a result of the formation of secondary quartz.

DISCUSSION

Micromorphological characteristics can be very useful in determining the degree of hydromorphism of a profile and its actual or past character. Sesquioxide segregations such as coatings, hypocoatings or quasicoatings,

and nodules have an especially good diagnostic value. Although differentiation between groundwater and surface water gleys is possible in many cases, insufficient comparative data are available to make unambiguous determinations. The presence of other features such as diatoms, newly formed typic minerals, etc. indicates specific soil conditions. Much comparative research on the micromorphological expression of hydromorphism in different soil types and under different climatic conditions is needed. The use of clear terminology, both for the micromorphological description and the classification of the soils and their water regimes, is of utmost importance.

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FUNDAMENTAL CHARACTERISTICS OF WETLAND SOILS

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Fundamental characteristics of wetland soils in the tropics are reviewed with reference to paddy soils in tropical Asia. Climate and physiography are the two controlling factors for the distribution of wetlands, most of which occur on young geologic formations of the late Pleistocene and Holocene in humid to perhumid climatic conditions.

Wetland soils are quite variable in material nature but are always high in clay activity, unlike tropical upland soils, which are dominated by low-activity clays. The status of the major nutrients in tropical wetland soils is not necessarily good, but it is better than that of upland soils.

Among the physical characteristics of wetland soils, immunity to soil erosion hazards is the most important, especially in tropical environments.

Wetlands occur widely, even in quite dry regions, but they are not distributed uniformly throughout the world. Tropical Asia, which occupies roughly one-sixteenth of the world's total land area, possesses more than one-third of the world's total potentially arable alluvial soils. Asia as a whole (excluding the USSR) has about two-thirds (or 192 million ha out of the world's 316 million ha) of such soils. Although "alluvial soil" is not used synonymously with wetland soil in the present paper, those figures suffice to show the unevenness of the distribution of wetlands.

Asia's large share of the world's wetlands has helped it support its very high population through the use of the land for rice cultivation. But wetlands in other parts of the world have been relatively less intensively used or have been left unused. The extent of wetlands in South America is not small, one survey has revealed that Brazil alone has about 25 million ha of wetlands that are potentially suited to paddy cultivation (A. S. Lopes, pers. comm.) and this figure

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will be much higher if the Peruvian and Colombian Amazon Basins are considered. Thus, there is still a high potential for wetland development, at least in South America and probably in some parts of Africa.

In this paper the fundamental characteristics of wetland soils are reviewed so that plans for reclamation and intensive management of wetland soils can be soundly based on them. Rice is assumed to be the main crop grown in wetlands.

GENERAL CHARACTERISTICS

Climate and physiography

A wetland soil in the present discussion is defined as a soil with an aquic moisture regime as described in Soil taxonomy (15). It is saturated by groundwater or by water of the capillary fringe for some time of the year. The occurrence of such a soil is conditioned by both climate and physiography. A humid climate, particularly with a concentration of rainfall during the rainy season, favors seasonal saturation of soil with water and seasonal flooding of low-lying lands. An abundance of low-lying land therefore contributes to the existence of wetland areas. Much of the wetlands in tropical Asia are the result of a combination of a humid climate with a heavy concentration of rainfall and an abundance of low-lying land such as floodplains, deltas, and wide coastal lowlands.

Wetlands are not, however, confined to low-lying lands. Under a heavy concentration of rainfall, even terraces and fans are flooded or saturated with water, as long as the land surface is level or depressional and soils are heavy-textured and impervious. Thus it is possible to generalize that most wetlands are distributed on late Pleistocene and Holocene sediments under a humid to perhumid climate.

Classification of wetland soils

Most wetland soils are classified as either Aquents or Aquepts, or as Histosols, where the decomposition of organic matter is retarded because of peraquic conditions. They are characterized by the absence of any well-defined diagnostic horizons that are the products of a long-term pedogenetic process. They may have an ochric or histic epipedon and a cambic subsurface horizon. In a word, they are totally immature or only weakly developed as soils and have poorly expressed profile morphology.

Other soils of some importance in wetlands are Aqualfs and Aquults on terraces. Aqualfs occur more frequently in areas with a subhumid climate, while Aquults occur in more humid climatic conditions.

Although aquic features are not clearly visible and the area is also limited, Vertisols occur in wetlands with montmorillonite-rich clayey sediments under a climate with a distinct dry season.

Further considerations pertinent to the classification of wetland soils at lower categories will be given at the end of the paper, after the discussion on the chemical and physical characteristics of wetland soils.

CHEMICAL CHARACTERISTICS

Material nature

The fact that most wetland soils occur in the most recent geological sediments and have very immature profile morphology implies that the soil characteristics are determined directly by the nature of the parent sediments. It follows further that the variability of wetland soils is quite wide because the nature of the parent materials is determined by local geology and by the degree of weathering in the catchment area or the milieu of sedimentation, or both.

To grasp the range of variability, Kawaguchi and Kyuma (5) attempted a classification of soil materials for 410 paddy soil samples taken from tropical Asian countries and set up 10 soil material classes on the basis of textural composition and total chemical composition. As shown in Table 1, the variability is very wide; the soils range from very siliceous material found in strongly weathered sandstone areas to base-rich materials with a high content of weatherable minerals originating from recent volcanic ejecta.

Table 2 gives the clay mineralogical composition of the paddy soils of different countries in tropical Asia (5, 8, 9, 10). The mean contents of 14 Å clays, dominated by smectites, are quite high in many countries, and thus the clays can by no means be said to be low in activity. This is clearly shown by the data for the CEC of 100 g of clay in the same table, the lowest mean value being 33.6 meq/100 g for Vietnam (Mekong Delta) and the highest mean being 64.1 meq/100 g for the Philippines. This point is important. Most upland soils in the tropics are said to be dominated by low-activity clays; therefore their management presents various difficulties. Wetland soils in the tropics are similar to temperate zone soils in their charge characteristics, which would make the transfer of technology from the temperate to the tropical countries easier.

Fertility characters

Several of the histograms prepared by Kawaguchi and Kyuma (5) are reproduced here to show the range of

Table 1. Mean mechanical and total chemical composition and some other related properties of the samples in each material class (5).

Class (no. of samples)		I (61)	II (68)	III (66)	IV (29)	V (42)	VI (31)	VII (25)	VIII (44)	IX (25)	X[a] (19)	Whole (410)
Sand	%	12.40	34.43	8.64	21.83	58.72	20.33	18.82	73.78	68.38	54.63	33.81
Silt	%	22.73	34.05	35.21	33.93	19.84	25.92	49.76	15.54	10.05	25.70	27.60
Clay	%	64.87	31.52	56.15	44.20	21.43	53.76	31.43	10.68	21.56	19.68	38.59
SiO_2	%	62.85	80.45	67.40	66.55	73.81	59.00	66.65	94.62	77.55	62.70	72.12
Fe_2O_3	%	9.90	3.07	5.71	7.69	4.51	11.95	6.71	0.82	5.41	6.89	5.96
Al_2O_3	%	22.12	12.78	21.53	19.25	14.58	20.98	18.31	3.45	11.87	18.41	16.38
CaO	%	1.31	0.39	0.46	1.95	2.03	3.22	1.58	0.22	0.98	6.89	1.42
MgO	%	0.90	0.38	0.94	1.23	0.95	1.57	1.98	0.05	0.68	2.28	0.92
TiO_2	%	0.22	0.06	0.06	0.18	0.11	0.31	0.10	0.02	0.14	0.16	0.12
K_2O	%	1.04	1.85	2.67	1.96	2.99	1.16	3.59	0.40	1.31	1.49	1.83
P_2O_5	%	0.12	0.09	0.13	0.15	0.15	0.22	0.13	0.06	0.12	0.24	0.13
pH		6.1	5.3	5.2	6.5	6.8	7.0	6.6	5.3	6.0	6.9	6.0
PBS	%	94.2	59.1	81.5	100.0	103.2	106.2	98.9	65.0	83.0	105.8	85.7
CEC	(meq/100 g)	31.1	12.3	20.4	26.7	13.9	34.4	15.4	4.2	10.3	15.5	18.6
7Å	%	43.1	52.4	46.7	32.6	36.8	37.3	32.4	70.1	63.0	29.3[a]	46.4[a]
10Å	%	5.0	19.2	20.9	12.4	20.2	3.9	28.2	5.1	8.2	12.3[a]	13.9[a]
14Å	%	51.9	28.5	32.4	55.0	43.0	58.9	39.4	24.8	28.8	58.4[a]	39.7[a]

[a]Because four samples in group X had no crystalline minerals, the means for the other samples were taken.

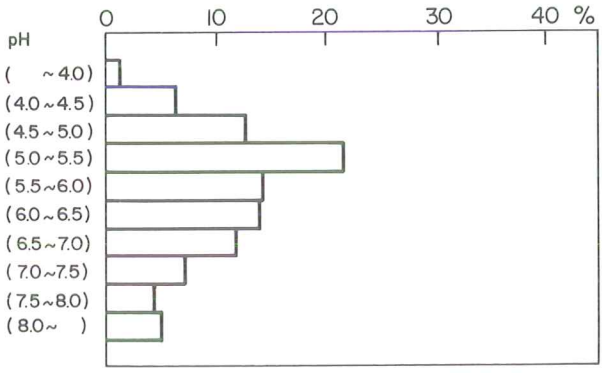
Table 2. Means and standard deviations for relative contents (%) of 7Å, 10Å, and 14Å minerals and for CEC of the clay fraction by country.

Country	No. of samples	Relative content (%)						CEC of clay (meq/100 g)
		7Å minerals		10Å minerals		14Å minerals		
		Mean	S. D.	Mean	S. D.	Mean	S. D.	
Bangladesh	53	34.3	10.7	29.2	14.4	36.5	13.6	40.8
Burma	50	26.9	7.4	17.3	6.5	55.8	10.7	48.1
Cambodia	16	60.6	19.2	4.1	8.5	35.3	17.8	42.1
India	73	34.7	16.4	23.7	8.2	41.5	20.6	56.0
Indonesia	44	46.6	29.7	0.7	15.3	52.7	30.5	51.0
Malaysia, East	36	35.2	14.2	33.5	17.6	31.3	12.7	49.6
Malaysia, West	41	59.4	22.2	9.0	2.6	31.6	23.4	34.5
Philippines	54	31.2	19.4	2.6	4.5	66.2	24.3	64.1
Sri Lanka	33	64.2	25.6	9.1	11.5	26.7	23.6	47.7
Thailand	80	59.2	16.5	12.9	12.0	27.9	15.5	39.2
Vietnam	49	47.2	9.4	33.1	7.7	19.8	5.2	33.6
Tropical Asia	529	43.7	20.8	16.8	15.1	38.7	22.9	46.4

variability of fertility indicators of wetland soils in the tropics.

pH. As shown in Figure 1, the mode was pH 5.0-5.5, but the overall mean for the 410 sample soils was 6.0. The country means were low for Peninsular (West) Malaysia (4.7), Thailand (5.2), and Cambodia (5.2). Later studies by Kyuma (8, 9, 10) indicated that paddy soils in the Mekong and Irrawaddi Deltas, as well as in the coastal lowlands of Sarawak, East Malaysia, were also quite acid, the mean values being 4.5, 4.8, and 4.5, respectively. The cause of the low pH values of coastal plain soils was explained by van Breemen (16) and may be applicable to the Mekong and Irrawaddi soils. The low pH of Malaysian paddy soils may be explained by the frequent occurrence of peaty soils.

The rest of the countries had high mean pH values, nearly equal to or higher than 6.0, which is much higher than the mean pH value of 5.4 for Japanese paddy



1. pH values of paddy soils in tropical Asia.

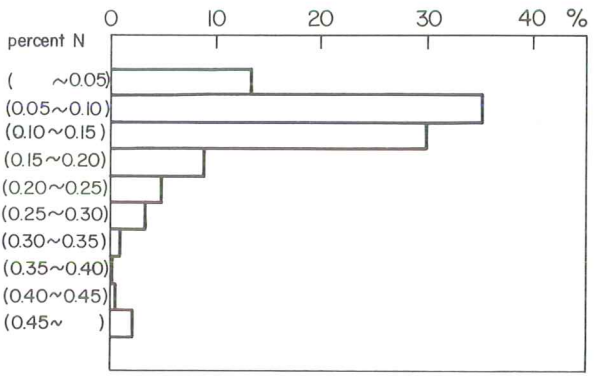
soils. The concentration of rainfall in half of the year, resulting in a large amount of runoff relative to percolation, and the alternation of the rainy and dry seasons explain the difference in the mean pH values between Japan and, for example, Sri Lanka, which has an even greater annual precipitation than Japan.

The occurrence of high-pH (>7) soils in wetlands is associated with the climate or the parent material, or both. Climatic influence is obvious from the fact that all the high-pH soils of Java, Indonesia, come from Central and East Java, where the climate is drier than in West Java. The effect of parent material is best seen in Bangladesh, where the climate is almost uniform throughout the country. All the high-pH soils occur in the region covered by recent Gangetic alluvia, which contain free $CaCO_3$. The occurrence of Vertisols with high pH among paddy soils is also conditioned by parent materials.

Soils with exceptionally low pH, below 4.5, are either peaty or of brackish sediment origin. Acid sulfate soils occur in many countries in Southeast Asia and pose great difficulty when used as paddy soils. The occurrence of a very large area of tropical peat is a specific feature of the Southeast Asian equatorial region. Reclamation of peat land also faces many difficulties.

Total nitrogen. As shown in Figure 2, about 78% of the samples studied contained total N only <0.15% of air-dry soil, and the overall mean for tropical Asian paddy soils was as low as 0.13%. The last figure may be compared with 0.29% for Japanese paddy soils. Obviously the potentially mineralizable N in most tropical Asian wetland soils is very low.

As the C-N ratio of paddy soils is invariably between 10 and 12, irrespective of tropical or temperate conditions, almost the same thing can be said of the total C content of the sample soils. In short, the



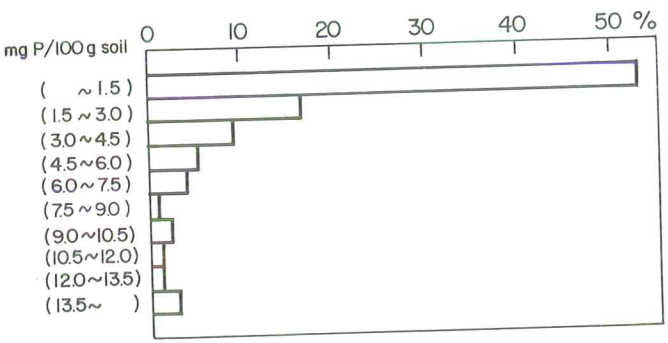
2. Total N content of paddy soils in tropical Asia.

organic matter reserve in tropical wetland soils is generally very low.

Climate and local relief appear to contribute to the accumulation of organic matter. Texture may also have some effect in determining the level of organic matter reserve. Among the paddy soils studied, those of India had the lowest mean, reflecting the drier climate, while those of Malaysia had an exceptionally high mean value because they included peaty soils.

Although the total N reserve is low, the N status of wetland soils is better than that of upland soils. First of all, the level of organic matter reserve is even lower for upland soils, giving paddy soils a relative advantage. Second, biological N fixation is more active in paddy fields or wetlands than in upland fields. Hauch (3) gave a range of 13-99 kg N/ha for paddy fields compared with 7-28 kg N/ha for ordinary (nonleguminous) upland fields. Azolla, blue-green algae, photosynthetic bacteria, and heterotrophs in the rhizosphere all contribute to N fixation in waterlogged paddy fields. Third, the leaching loss of N applied or released by mineralization of soil organic matter is less in the wetlands than in the uplands because ammoniacal N can stay adsorbed on the exchange complex. However, losses due to NH_3 volatilization and denitrification appear considerably greater in wetland soils than in the uplands.

Phosphorus. Available P determined by the Kurtz No. 2 method is shown in Figure 3. More than half of the total number of the samples contained only <6.6 ppm available P, obviously far below the required level of rice. According to Komoto (7), at least 60 ppm of Bray No. 2 P are required in the soil to attain a normal yield of rice in the warmer regions of Japan. These P-deficient soils occur in areas with siliceous parent materials such as Cambodia, the east coast of Peninsular Malaysia, Thailand, and Sri Lanka. The overall mean was only 38 ppm, much less than the mean of 129 ppm for Japanese paddy soils.

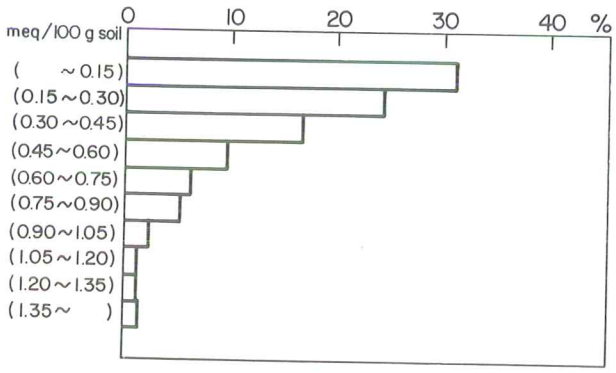


3. Available P (Bray-P) content of paddy soils in tropical Asia.

A low available P status may be caused either by high P-sorption capacity of the soil or by a low absolute content of P. As P-sorption capacity is not high for most wetland soils in tropical Asia, the main cause of the low availability of P is the low absolute content of P in the soil. Kawaguchi and Kyuma (5) found that nearly one-fourth of the 410 paddy soil samples contained less than 400 ppm total P, which is thought to be critically low for normal rice growth even at the present low level of rice yield.

In the case of P, again paddy soils have an advantage over upland soils. Because of the aquic or reducing moisture regime, a part of the fixed or occluded P is released during Fe reduction. Also, a rise in pH in acid soils and a lowering of pH in alkaline soils renders the main forms of fixed PO_4^{2-} more soluble as a result of soil reduction. In short, PO_4^{2-} availability is kept higher in wetlands than in uplands for the same total content of soil P.

Potassium. Figure 4 shows a histogram of exchangeable K. According to Kemmler (6), an exchangeable K level below 0.15 meq/100 g soil is regarded as low, and about 30% of the total samples fell into this category. But the mean content of exchangeable K for tropical Asian paddy soils (0.4 meq/100 g soil) was not lower than that for Japanese paddy soils. Furthermore, for an element with abundant reserves in the soil, like K, the rate of release from soil minerals should be considered. If we note a higher rate of release by weathering under tropical conditions, the availability of K could be higher in tropical than in Japanese paddy soils. In addition, some supply from irrigation water can be expected. In one study in Japan, irrigation water supplied 18% of the requirement of rice. Of course, the value varies depending on the conditions, but it is always quite substantial. What has been stated here, however, does not rule out the possibility



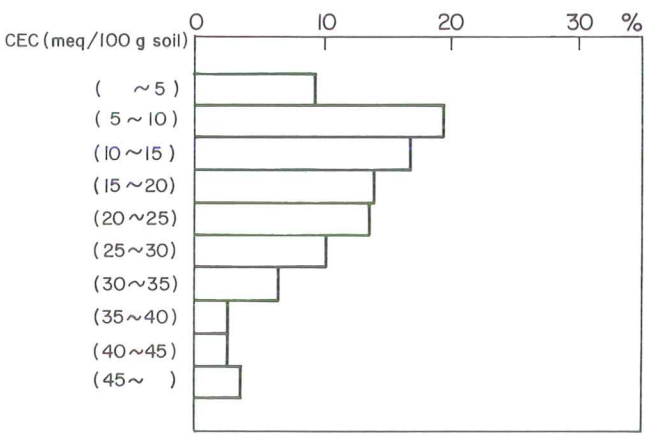
4. Exchangeable K content of paddy soils in tropical Asia.

of the occurrence of K deficiency in rice. Tanaka and Yoshida (13) reported incidences of K deficiency in tropical Asian countries.

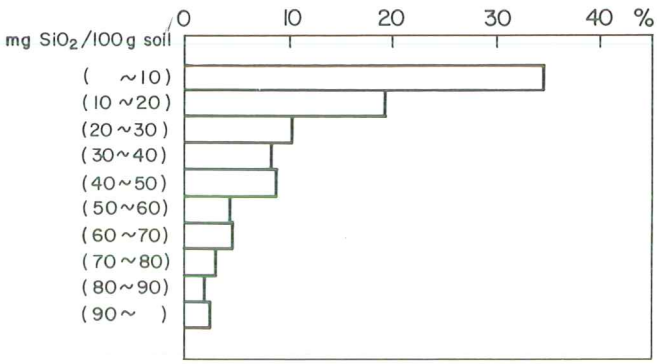
The above discussions also apply to other basic cations, Ca and Mg. Generally the contribution of irrigation or floodwater to rice nutrition is much higher.

CEC. As shown in Figure 5, CEC showed a positive skew, and the overall mean of 18.6 meq/100 g soil was far from the mode, which was 5-10 meq/100 g. If we note that low CEC is invariably found in sandy-textured soils, we can confirm here again what was earlier said about clay activity. The paddy soils of Java, Indonesia, and the Philippines are particularly rich in good-quality clays and have high mean CEC values. Most wetland soils in those countries are derived from relatively unweathered basic volcanic ejecta.

Available silica. Silica is thought to be nonessential to most agricultural crops, but it is regarded as essential to rice. The proper content of silica in the leaves and stalks of rice gives the plant resistance to blast and to lodging, thus making a higher N dose and accordingly a higher yield possible. Figure 6 shows available silica determined with pH 4-acetic acid extract (4). In Japan, 10.5 mg/100 g soil is considered a threshold value below which application of silicate slag always results in a positive response. The same criterion may not be applicable to tropical paddy soils, because the rate of silica release from soil minerals or the weathering intensity appears higher in the tropics. This might also explain the high overall mean of available silica content, exceeding that of the Japanese mean, which is already high because of the wide distribution of volcanic ashes. Irrigation or floodwater also supplies a substantial amount of available silica. Silica deficiencies are



5. Cation exchange capacity of paddy soils in tropical Asia.



6. Available silica content of paddy soils in tropical Asia.

feared only for psammentic soils and Histosols in the tropical wetlands.

Country means. Table 3 gives country means of fertility characters of wetland soils. The means for tropical Asia were computed for a new set of 529 samples, including Vietnam (the Mekong Delta), East Malaysia (Sarawak), and additional samples from Burma (the Irrawaddi Delta). Because of the low pH of the newly added soil samples, the overall mean pH was lowered from 6.0 for the previous set of 410 soils to 5.6. Similarly, some shifts occurred in the means of characters covarying with pH.

For comparison, the means for paddy soils of Mediterranean countries (Italy, Spain, and Portugal) and of Japan are also cited in Table 3. As stated, the CEC of tropical Asian wetland soils is by no means low even when compared with that of temperate soils. Also, judged from the CN ratios, the tropical and temperate soils do not differ in the nature of their organic matter. The most conspicuous difference between tropical Asia and Japan is in P status, which would reflect human interference.

Probable nutritional disorders

Only a few nutritional disorders that are probably more frequently encountered in the course of wetland utilization are dealt with here.

Akiochi. Akiochi is a Japanese word meaning autumnal decline in plant vigor. With heavy doses of fertilizer, rice plants in Japan grow vigorously until midsummer, but toward the end of summer their growth declines and a very unsatisfactory yield results. The type of soil that shows this phenomenon is normally a whitish-colored sandy soil. A process called "ferrolysis" operating in seasonally submerged wetland soils could lead to the formation of akiochi-inclined soil (1). A low content of free Fe oxide in the soil is most directly linked to akiochi, but is also indicative of

Table 3. Country means for various fertility characters.

Country	No. of samples	pH	Total C (%)	Total N (%)	C:N	NH_4-N (mg/100 g)	(% of total N	Total P (P_2O_5 mg/100 g)	Bray-P (P_2O_5 mg/100 g)	HCl-P (P_2O_5 mg/100 g)	Exchangeable					Available SiO_2 (mg/100 g)
											CEC (meq/100 g)	Ca (meq/100 g)	Mg (meq/100 g)	Na (meq/100 g)	K (meq/100 g)	
Bangladesh	53	6.1	1.18	0.13	8.7	6.1	4.5	84.1	3.8	21.0	12.9	7.8	2.7	0.9	0.3	12.9
Burma	50	4.8	1.18	0.12	11.3	3.5	2.9	58.2	1.0	7.8	20.5	7.2	8.4	1.5	0.4	13.3
Cambodia	16	5.2	1.09	0.10	10.7	4.0	5.1	44.3	0.6	1.9	14.6	5.4	3.2	0.3	0.2	11.3
India	73	7.0	0.85	0.08	11.7	2.7	3.9	92.0	8.1	21.9	22.0	15.0	6.5	2.4	0.5	34.7
Indonesia	44	6.6	1.39	0.12	12.6	14.1	12.4	133.7	2.4	10.0	26.1	17.8	6.3	1.5	0.4	62.9
Malaysia, East	36	4.5	9.66	0.64	14.7	30.2	5.8	101.5	1.1	5.0	23.0	3.5	3.8	1.2	0.4	10.3
Malaysia, West	41	4.7	3.36	0.28	11.8	14.9	6.3	80.3	3.7	8.2	15.9	3.9	5.2	1.5	0.4	10.4
Philippines	54	6.4	1.66	0.15	11.7	17.2	10.8	113.6	3.7	13.4	27.0	14.8	9.3	2.2	0.5	45.4
Sri Lanka	33	5.9	1.41	0.13	10.5	8.4	7.0	72.5	1.4	9.0	11.5	5.4	3.5	0.5	0.2	21.6
Thailand	80	5.2	1.05	0.09	11.3	5.2	6.6	44.2	1.4	4.7	14.4	7.2	4.3	1.4	0.3	12.2
Vietnam	49	4.5	2.49	0.20	11.9	7.7	3.7	76.4	1.2	5.1	18.8	7.1	5.4	1.2	0.4	15.4
Tropical Asia mean	529	5.6	2.07	0.17	11.5	9.6	6.2	82.1	3.0	10.9	19.1	9.3	5.5	1.5	0.4	23.7
Mediterannean countries	62	6.8	1.82	0.16	10.6	7.6	4.9	103.8	7.2	–	18.0	15.9	4.6	1.0	0.6	23.9
Japan	84	5.4	3.33	0.29	11.6	17.5	6.5	220.4	12.9	46.5	20.3	9.3	2.8	0.4	0.4	19.5

the general paucity of nutrient elements and of the poor quality of clay minerals. Normally, akiochi-inclined soils are also poor in K, Ca, Mg, Mn, silica, and even micronutrients. The phrase "degraded paddy soil," often used to denote akiochi-affected soil, is therefore quite proper.

Iron toxicity. Iron toxicity has been reported in two types of soils, one being acid sulfate soil and the other being strongly depleted wetland soil in areas dominated by highly weathered upland soils. In the latter, poor nutritional status and H_2S injury seem to be the primary cause. Moormann and van Breemen (11) examined the interflow water from surrounding areas with Oxisols and Ultisols. In acid sulfate soils strong acidity and Al toxicity are the primary causes and P deficiency, poor general nutritional status, and at times high salinity are the secondary causes that weaken the built-in protective mechanism of the rice root to exclude excessive Fe^{2-}.

Zinc deficiency. Zinc deficiency used to be a very minor problem in the traditional rice-growing areas, but now it is quite widespread in newly reclaimed paddy soils with irrigation under subhumid to semiarid climatic conditions. Most soils affected by Zn deficiency are calcareous or saline, and sodic with alkaline pH. Strongly reduced soils in swampy wetlands are also reported to show Zn deficiency. Zinc carbonate and ZnS are the probable forms of Zn that regulate its solubility in reduced paddy soils. About 2 million ha of paddy soils are Zn deficient (12).

Copper deficiency. In organic or peat soils, Cu deficiency is sometimes suspected to be responsible for poor performance of rice, although the literature has not definitely verified this suspicion. Driessen (2) suggested that the sterility of rice on deep peat could be attributable to the uncoupling of oxidative phosphorylation in a Cu-deficient environment, as exemplified by peat lands in Kalimantan and Sumatra, Indonesia.

PHYSICAL CHARACTERISTICS OF WETLAND SOILS

The textural composition of paddy soils in tropical Asian countries is shown in Table 4. Soil texture is generally fine in the tropical wetlands. Soils containing >45% clay amount to 40% of all the paddy soils studied by Kawaguchi and Kyuma (5). This clayey texture, combined with a low organic matter content, indicates generally poor physical properties. In the monsoonal climate, wetland soils are too wet during the rainy season and too dry during the dry season; soils become too sticky and plastic during the wet season and too hard and difficult to work with during the dry.

Table 4. Means and standard deviations for textural composition by country.

Country	No. of samples	Sand		Silt		Clay	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Bangladesh	53	25.6	20.0	42.8	13.1	31.6	17.2
Burma	50	14.7	14.1	42.7	11.1	42.6	18.5
Cambodia	16	33.9	25.5	31.4	12.7	34.7	24.3
India	73	36.4	22.8	24.3	11.2	39.3	19.6
Indonesia	44	22.5	18.3	26.3	10.8	51.2	24.2
Malaysia, East	36	14.4	18.1	39.2	12.9	46.4	16.6
Malaysia, West	41	22.5	22.0	31.3	10.6	46.1	16.1
Philippines	54	27.1	20.8	30.8	9.2	42.1	18.8
Sri Lanka	33	68.3	20.2	7.6	6.0	24.1	15.8
Thailand	80	38.2	29.3	25.2	11.1	36.7	24.6
Vietnam	49	9.4	14.4	34.6	8.3	56.0	12.0
Tropical Asia	529	28.3	25.5	30.5	13.9	41.2	20.8

Especially in rice-based multiple cropping, cultivation of upland crops is difficult because puddling for rice destroys any existing soil structure. Thus, physical properties of clayey wetland soils often pose severe constraints to the cultivation of upland crops. Lighter-textured soils are preferred for use in such cropping systems.

For rice cultivation itself, however, soil physical properties are relatively unimportant as long as sufficient water is available. Under submerged conditions even very clayey soils are comparatively easily manageable with draft animals. Practically no considerations are necessary in balancing water-holding and permeability requirements, which are, however, vital in managing soils for upland crops. This is another reason why rice is preferred to upland crops in the wetlands.

It must be stressed that the wetland soils are immune to soil erosion hazards. The greatest difficulty in the sustained use of tropical upland soils is the loss of topsoil due to soil erosion. Tropical rainfall is so erosive that even level land with soils of low erodibility does not seem very safe. Immunity to erosion gives wetland soils in the tropics a very great advantage in making preservation of soil fertility possible. Rice cultivation that requires terracing, leveling, and bunding of the land for submergence fortifies this advantage.

CONSIDERATIONS PERTINENT TO THE CLASSIFICATION OF WETLAND SOILS AT LOWER CATEGORIES

In relation to what has been discussed, some pertinent points to be considered by one attempting to classify

wetland soils at lower categories are given below.

- Material nature should be appropriately evaluated and incorporated into the classification.

  Because most wetland soils are derived from the sediments of the most recent geological origin, they are young as a soil and have undergone little or no pedogenetic modifications. Thus, the nature of wetland soils is primarily governed by the nature of their parent sediments.

  In addition, the variability of material nature is by far the greatest in wetland soils. It is conditioned by the geology and the degree of weathering in the catchment area or the milieu of sedimentation, or by both. At one extreme, fresh volcanic ejecta are laid down in wetlands, as, for example, on the island of Java, Indonesia, while at the other extreme there are such cases as those mentioned in the Seventh Approximation (14), where "Chemically and mineralogically, the materials in an oxic horizon may be indistinguishable from materials at comparable depths in Entisols." It should be further noted that the range of variability is wider in the tropics than elsewhere.

  In the present system of Soil taxonomy (15), the material nature of a soil is considered at the family level by such differentiae as particle size class and mineralogy class. But as far as the latter is concerned, most wetland soils are classified as "mixed," which tells hardly anything useful in judging soil quality for plant growth. There must be further elaboration to incorporate more useful information on soil material nature into classification.

- Surface soil characteristics should be properly considered.

  In Soil taxonomy, the differentiating characteristics are almost always taken from the subsoils to keep the system unaffected by human activity in the surface soil or by truncation of surface soil because of erosion. This is justifiable where there are genetic relationships between the surface soil and the subsoil. In such a case, it may be possible to some extent to judge surface soil quality from the subsoil characteristics. But in most wetland soils derived from alluvial sediments, there are no genetic relationships between any two sedimentary beds. Moreover, there is no danger of losing surface soil by erosion, nor are there any morphological features to be lost by cultivation practices. Yet, even for wetland soils on alluvia, the control section for classification is

set at depths between 25 cm and 100 cm. Thus, the soil characteristics taken for classification have little relevance to the quality of soil as the medium of crop growth.

The point made here may not be easily considered in Soil taxonomy, because the consistency of the system has to be given high priority. Then there is a need to cover the drawback by some means. Some sort of technical classification based on the surface soil characteristics should be worked out.

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AGRONOMIC TAXONOMY FOR WETLAND SOILS

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An interpretation of the Fertility Capability Classification (FCC) system was made for soils with aquic or anthraquic soil moisture regimes to relate soil classification with soil productivity parameters for flooded rice production. It was necessary to include one additional condition modifier in the FCC: a g* modifier for constantly flooded soils. The FCC modifier was directly applicable to identification of specific attributes for flooded rice production such as difficulty of puddling, traffic pan formation potential, structural regeneration after drying, deep vs. shallow organic soils, low inherent potentiality, ferrolyzed or degraded paddy soils, acid sulfate, saline, sodic, and skeletal soils. Specific FCC parameters are directly related to most physiological disorders of the rice plant except I and B toxicity. Iron toxicity, caused by Fe-rich interflow from adjacent uplands, requires an FCC classification of such upland soils.

After converting the FAO-UNESCO Soil map of the world into FCC for three developing regions of the world, it can be concluded that the most extensive constraints to rice production in the 550 million ha of natural wetlands are physical rather than chemical. The main physical constraints are a dry season, puddling difficulties, structure regeneration, and low bearing capacity of organic soils. Approximately 19% of the wetlands are affected by severe chemical constraints caused by salinity (37 million ha), strong acidity (22 million ha), low nutrient reserves (19 million ha), acid sulfate soils (13 million ha), calcareous soils (6 million ha), sodic soils (4 million ha), low cation exchange capacity (3 million ha), and gravel (1 million ha).

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> Soil constraints to potential flooded rice production appear less severe in the wetlands of Latin America and Africa than in the Asian wetlands. The potential for opening major areas for rice production in these two continents may be an important component of a world rice strategy during the next century.

The purpose of this paper is to relate some of the main characteristics of soils with aquic moisture regimes to their capability for rice production. Throughout the world, a considerable gap exists between the subdisciplines of pedology and agronomy. Pedologists attempt to classify soils according to their more permanent properties, which occur mainly in the subsoil. Agronomists, conscious that most soil parameters affecting crop yields are located in the topsoil, look at the soil quite differently. Communication is often difficult, and in many instances both groups tacitly agree politely to ignore each other. Communication difficulties have been exacerbated by the advent of quantitative soil classification systems that provide pedologists a solid basis for international communication, while agronomists, lacking a common reference base, relate to each other with qualitative, often idiosyncratic terminology. Soil scientists working with rice in wetland areas are no exception.

As the authors began to review the pedological and agronomic literature, it became clear that the basis for an agronomic taxonomy of wetland soils was implied in publications by Moormann and Dudal (25), Tanaka and Yoshida (34), Kawaguchi and Kyuma (23), Moormann and van Breemen (26), IRRI (20, 21), TARC (35), and others. What is needed is a framework in which relationships can be made explicit and described in quantitative terms. Such a framework should be potentially acceptable to both pedologists and agronomists working with wetland soils. The Fertility Capability Classification (FCC) system appears to be one possibility. Its use as a means to relate wetland soil properties to rice requirements is presented in this paper as a working hypothesis, subject to modifications the participants of this workshop may consider appropriate.

FCC is a technical system for grouping soils according to the kinds of problems they present for agronomic management (5). It is based on quantitative topsoil and subsoil parameters directly relevant to plant growth, mostly derived from class limits of Soil taxonomy (36) or of the legend of the FAO-UNESCO Soil map of the world (9). The latest FCC version (33) is shown in Table 1. This version also includes sample interpretations of FCC classes, conversions of soil mapping units into FCC units, and the system's appli-

cability to the FAO Land evaluation guidelines (11). Several of the FCC parameters described in Table 1 can be analyzed by alternative methods. They are designed to allow the FCC system to be compatible with existing soil surveys, soil classification systems, and soil fertility methodologies. This system is open-ended, and

Table 1. The FCC system (33).

Type (texture of plow-layer or surface 20 cm, whichever is shallower)

S = sandy topsoils: loamy sands and sands (by USDA definition);
L = loamy topsoils: <35% clay but not loamy sand or sand;
C = clayey topsoils: >35% clay;
O organic soils: <20% O. M. to a depth of 50 cm or more.

Substrata type (texture of subsoil).[a]

S = sandy subsoil: texture as in type;
L = loamy subsoil: texture as in type;
C = clayey subsoil: texture as in type;
R = rock or other hard root-restricting layer.

Modifiers.[b]

g = (gley) = soil or mottles <2 chroma within 60 cm of the soil surface and below all Al horizons, or soil saturated with water for >60 days in most years;

d = (dry) = ustic, aridic, or xeric soil moisture regimes (subsoil dry > 90 cumulative days per year within 20- to 60-cm depth);

k = (low in reserves): <10% weatherable minerals in silt and sand fraction within 05 cm of the soil surface, or exchangeable K <0.20 meq/100 g, or K <2% of Σbases; if bases <10 meq/100 g;

e = (low cation exchange capacity): applies only to plow layer or surface 20 cm, whichever is shallower; CEC <4 meq/100 g soil by Σ bases + KCl-extractable Al (effective CEC), or CEC <7 meq/100 g soil by Σ cations at pH 7, or CEC <10 meq/100 g soil by Σ cations + Al + H at pH 8.2;

a = (aluminum toxicity): >60% Al-saturation of the effective CEC within 50 cm of the soil surface, or >67% acidity saturation of CEC by Σ cations at pH 7 within 50 cm of the soil surface, or >86% acidity saturation of CEC by Σ cations at pH 8.2 within 50 cm of the soil surface, or pH <5.0 in 1:1 H_2O within 50 cm, except in organic soils where pH must be less than 4.7;

h = (acid) = 10-60% Al-saturation of the effective CEC within 50 cm of soil surface, or pH in 1:1 H_2O between 5.0 and 6.0;

b = (basic reaction): free $CaCO_3$ within 50 cm of soil surface (effervescence with HCl), or pH >7.3;

i = (high P-fixation by iron): % free Fe_2O_3/% clay > 0.15 and more than 35% clay, or hues of 7.5 YR or redder and granular structure. This modifier is used only in clay (C) types; it applies only to plow-layer or surface 20 cm of soil surface, whichever is shallower.

x = (X-ray amorphous): pH >10 in 1*N* NaF[c], or positive to field NaF test, or other indirect evidences of allophane dominance in the clay fraction;

v = (vertisol): very sticky plastic clay: >35% clay and >50% of 2:1 expanding clays, or severe topsoil shrinking and swelling;

s = (salinity): > 4 mmho/cm of electrical conductivity of saturated extract at 25°C within 1 m of the soil surface;

n (natric): > 15% Na-saturation of CEC within 50 cm of the soil surface;

c = (cat clay): pH in 1:1 H_2O is < 3.5 after drying and jarosite mottles with hues of 2.5 Y or yellower and chromas 6 or more are present within 60 cm of the soil surface;

= (gravel): a prime (') denotes 15-35% gravel or coarser (> 2 mm) particles by volume to any type or substrata type texture (example: **S'L** = gravelly, sand over (loamy; **SL'** = sandy over gravelly loam); two prime marks (") denote more than 35% gravel or coarser particles (> 2 mm) by volume in any type or substrata type (example: **LC'** = loamy over clayey skeletal, **L'C"** = gravelly loam over clayey skeletal);

% = (slope): where it is desirable to show slope with the FCC, the slope range percentage can be placed in parentheses after the last condition modifier (example: **Sb** (1-6%) = uniformly sandy soil, calcareous in reaction, 1-6% slope).

[a]Used only if there is a marked textural change from the surface of if a hard root-restricting layer is encountered within 50 cm. [b]Where more than one criterion is listed for each modifier, only one must be met. The criterion listed first is the most desirable and should be used if data are available. Subsequent criteria are presented for use where data are limited. [c]10.7 is considered a better limit and the user should carefully titrate the NaF solution to pH 8.2 before use. The soils are classified by determining whether the characteristic is present or not. Most the quantitative limits are criteria present in *Soil taxonomy* (36). The FCC unit then lists the type and substrata type (if present) in capital letters, and the modifiers in lower case letters, the gravel modifier as a prime (') and the slope, if desired, in parentheses.

additional features considered locally important can be added as prime (') or asterisk (*) (4). The authors have resisted adding condition modifiers, such as one for organic matter, if their effect cannot be quantified in relation to plant growth. Also, soil test parameters are excluded, because these values can be readily altered by management.

RICE PROBLEM SOILS AND NUTRITIONAL DISORDERS

Many pedologists approach soil constraints in wetland areas by focusing on problem soils, while agronomists list a series of nutritional disorders of the rice plants, often characterized by local names. The most frequently cited problem soils for rice production gleaned from reviews by Bhumbla and Abrol (1), Brinkman (2), Briones (3), Driessen (7), Goswami (18), Panichapong (28), Ponnamperuma and Bandyopadhya (30), van Breemen (37), van Breemen and Moormann (38), van Breemen and Pons (39), and Zahari et al (40) are acid sulfate soils, peat soils, saline and alkali soils, ferrolyzed or degraded paddy soils, and skeletal soils. The translation of these terms into Soil taxonomy or the FAO-UNESCO Legend is straightforward for the acid sulfate soils (Sulfaquents, Sulfaquepts, Sulfic Tropaquepts, Thionic Fluvisols) and peat soils (Histosols). Saline and alkali soils with aquic soil moisture regimes fall into several soil groups, the Halaquepts being more important for saline soils and perhaps the Natraqualfs for sodic soils. Ferrolyzed or degraded paddy soils are often classified as Aquults according to van Breemen (37). Skeletal soils containing more than 35% gravel or rock fragments cover 16% of Thailand; those used for rice cultivation are also classified as Aquults (28).

Agronomists, soil chemists, and plant physiologists view the same problem from the plant's point of view. Tanaka and Yoshida (34) list 14 nutritional disorders and their relationship to soil parameters (Table 2). Local names such as bronzing, akiochi, akagare, khaira, hadda, tayataya, and many others from Africa and Latin America are commonly used in the literature to describe such disorders.

Estimates of the geographical extent and distribution of these problem soils are seldom clearly established. The same applies to the extent and distribution of the nutritional disorders, which are often based on samplings of individual farmer fields.

FCC INTERPRETATION FOR WETLAND SOILS

The FCC system described in Table 1 is not crop specific. Moormann and van Breemen (26) state two advantages of the FCC approach: 1) most data can be gathered in the field or by careful interpretation of good soil maps, and 2) relatively simple laboratory facilities are required. Moormann and van Breemen further state that FCC must be adapted to rice growing in wetland environments.

Wetland soils are directly identified in the FCC system by the g modifier, which is defined almost exactly as the aquic soil moisture regime in Soil taxonomy. Non-g soils, soils without an aquic moisture regime on man-made bench terraces in steeplands of Southeast Asia, are also extensively used. Such "anthropic wetlands" have many characteristics in common with natural wetlands. These soils, therefore, are separately discussed in this paper.

Soils that lack an aquic moisture regime and are grown to upland rice are excluded from further consideration. FCC interpretations for upland rice in such soils should build on those published previously (33), giving proper consideration to the high tolerance for Al of many upland rice varieties.

An analysis of the literature, particularly the work of Kawaguchi and Kyuma (23) and Moormann and van Breemen (26), led us to conclude that one additional condition modifier is needed to adapt the FCC system to wetland soils: a modifier for constantly flooded soils with what may be called the peraquic soil moisture regime. The proposed new modifier is defined as follows.

> g* = (pergleyic): Soil profile saturated with water for more than 200 days per year with no evidence of brownish or reddish mottles indicative of oxidized Fe compounds within the top 50 cm

The possibilities of additional modifiers to denote low inherent potentiality (23), traffic pan

Table 2. Classification of nutritional disorders in Asia.[a]

Soil		Soil condition	Disorder	Local name
Very low pH		Acid sulfate soil	Iron toxicity	Bronzing
Low pH	High in active iron	Low in organic matter	Phosphorus deficiency combined with iron toxicity	
		High in organic matter		
		High in iodine	Iodine toxicity combined with phosphorus deficiency	Akagare Type III
		High in manganese	Manganese toxicity	
	Low in active iron and exchangeable cations	Low in potassium	Iron toxicity interacted with potassium deficiency	Bronzing Akagare Type I
		Low in bases and silica, with sulfate application	Imbalance of nutrients associated with hydrogen sulfide toxicity	Akiochi
High pH		High in calcium	Phosphorus deficiency Iron deficiency Zinc deficiency	Khaira Hadda Taya-taya Akagare Type II
		High in calcium and low in potassium	Potassium deficiency associated with high calcium	
		High in sodium	Salinity problem Iron deficiency Boron toxicity	

[a]Source: Tanaka and Yoshida (34).

formation, difficulty of puddling, and structure regeneration for rotating rice with other crops were found unnecessary because existing FCC parameters could be used to interpret these important factors. All problem soils and most nutritional disorders were readily identifiable by FCC units. The exceptions are I and B toxicities. Iron toxicity used by interflow of Fe-rich seepage requires an FCC class for the adjacent soils that are the interflow source. The FCC system, therefore, can be reinterpreted for soils with aquic soil moisture regimes, as follows. Sample interpretations for type and substrata type are shown in Table 3 and those for condition modifiers in Table 4.

Type and substrata type

The FCC system lists topsoil and subsoil texture in

Table 3. Sample interpretations of FCC type and substrata types for rice cultivation in an aquic soil moisture regime.

Type	Interpretation
S:	High in infiltration, low water-holding capacity, more difficult to do thorough puddling; traffic pans infrequent; relatively easy to regenerate structure for rotation with other crops. Level of management (nutrients and water) required for high rice yields is higher than in L or C soils.
L:	Medium infiltration, medium water-holding capacity, usually easy to puddle (except Lx), and medium difficulty in regenerating structure. Traffic pans important in these soils except for Lx. L soils are generally more productive for rice than S soils and less than C soils, provided condition modifiers are similar.
C:	Low in infiltration rates, high water-holding capacity (except Ci), easy to puddle and difficult to regenerate previous structure (except Ci); traffic pans not common. Generally higher productivity for rice than L or S soils provided condition modifiers are similar.
O:	Deep organic or peat soils, with little to no potential for rice production.
OC, OL, or OS:	Shallow organic soils with a mineral layer of less than 50-cm depth. Potential for rice production depends on depth and properties of mineral layer. Low bearing capacity; Cu, Mo, and K deficiencies common.
SL, SC:	Somewhat better water-holding capacity and thus better suitability for rice production than S soils.

the first and second categorical order because of their major importance to crop production. The FCC system has only three textural classes (S = sandy, L = loamy, C = clayey), which together with O (organic) and R (rock or hard root restricting layer) form the type-substrata type combinations shown in Table 1. If no marked textural change occurs within the top 50 cm, the type-substrata type is indicated with one letter (S, L, C, O). If there is such a change, two capital letters are used, for example SC for a sandy topsoil over a clayey subsoil or OC for a 20-cm deep peat material underlain by a clayey mineral soil.

Texture. The importance of texture to rice production in aquic soil moisture regimes is well acknowledged in the literature. Moormann and Dudal (25) cite earlier reports from China, Vietnam, and Indonesia asserting that C or L textures are superior to S textures for rice production. More recent observations in northeast Thailand and Japan led Moormann and van Breemen (26) to confirm that L or C soils are generally superior to S soils. These authors further indicate that high rice yields can be obtained in S soils only when water and nutrients are not limiting. S soils also require more precision in the timing of fertilizer

Table 4. Sample interpretations of FCC condition modifiers for rice cultivation in aquic soil moisture regime.[a]

Modifier	Limitations or management requirements
g =	Defines wetland soils. Preferred moisture regime for rice cultivation.
g* =	Prolonged submergence causes Zn deficiency.
d =	Topsoil moisture limited during dry season unless irrigated. Generally only one rainfed rice crop can be grown a year. Irrigated rice during the dry season has higher yield potential and responds to higher N rates.
k =	Low inherent fertility because of low reserves of weatherable minerals. Management levels higher than in soils without this modifier. Potential K deficiency depending on base contents of irrigation water.
e =	Low ECEC reflects less gradual N release, more exacting N management. Identifies degraded paddy soils with **SLa** or **LCa** and low organic matter contents. If so, potential H_2S toxicity can occur if $(NH_4)_2SO_4$ is used as N source. Potential Fe toxicity if adjacent uplands have Fe-rich soils.
a =	Aluminum toxicity will occur in aerobic layers. Soil test for identifying P deficiency recommended.
h =	Optimum aerobic pH for flooded rice production. Potential P deficiency with continuous rice cropping.
b =	High pH may induce Fe deficiency when aerobic and Zn deficiency when waterlogged. High N volatilization loss potential from broadcast N applications. NH_4^+ fixation by 2:1 clays possible. Mollusk shells indicative of Zn deficiency.
i =	High P fixation by Fe; P deficiency likely; Fe toxicity potential; soils difficult to puddle and will regenerate original structure rapidly. Interflow from **Ci** uplands may cause Fe toxicity to e soils with lower topographic position.
x =	Volcanic materials indicate high inherent fertility with no potential Si deficiency; N and P deficiencies common and soil may fix large quantities of P; soils difficult to puddle and will regenerate original structure rapidly.
v =	Soils will shrink and crack when dry, causing excessive percolation losses afterwards. Easy to puddle but difficult to regenerate structure. P deficiency suspect and should be determined by soil tests. Soils fix applied NH_4 and release it later to the rice crop (a positive-attribute). Cracks, however, may not close after drying and subsequent flooding, increasing percolation and exacerbating N losses.
g =	Defines saline soils. Drainage needed but must consider conductivity of irrigation water.
n =	Defines alkali soils. Reclaiming with drainage and gypsum applications may be needed.
c =	Acid-sulfate soils causing Fe and S toxicity when anaerobic and Al toxicity when aerobic. Depth at which c modifier occurs determines feasibility of rice production. Strong P deficiency likely and Al toxicity when aerobic.
' =	Presence of gravel limits land preparation and water-holding capacity.
" =	Skeletal soils with limited potential for rice production.
% =	The higher the % slope, the narrower the paddies and the higher the rise between terraces.

[a]When only one modifier is included in the FCC unit, the above limitations or management requirements apply to the soil. Interpretations may differ when two or more modifiers are present simultaneously or when textural types are different.

application, which often results in higher costs of production than L or C soils to produce similar rice yields. Moormann and van Breemen also indicated that S soils with a heavier subsoil are generally more productive than soils that are sandy throughout. In FCC terminology, SL or SC soils are easier to manage than S soils.

In Iloilo, Philippines, Magbanua et al (24) also found that C soils are more productive than L soils for

rice. In their classification of 410 paddy rice soils of tropical Asia, Kawaguchi and Kyuma (23) also provided higher ratings to L and C soils. The textural class distribution of seven tropical Asian countries indicates a preponderence over S soils of L and C soils where rice is grown (Table 5). Only Sri Lanka and Thailand have a high percentage of S soils. The above-mentioned constraints for S soils are, therefore, more important in these two countries than in others in Southeast Asia.

Organic soils. Soils with more than 20% organic matter, called peats, mucks, or Histosols, can be divided into two groups for rice production: the deep ones with the organic layer extending to a depth of 50 cm or more, and the shallow ones, with a mineral horizon within 20 cm of the surface. Attempts to cultivate rice in the deep Histosols have met with very limited success, while cultivation is possible in the shallow organics (26). The FCC system neatly distinguishes these two groups, the deep organics being O soils while the shallow organics over a mineral soil are classified as OC, OL, or OS. Clayey mineral soils underlie most shallow Histosols. These OC soils, however, have considerable limitations for rice production because of their low bearing capacity and nutritional deficiencies (Table 3). Many OC soils have high levels of S if the mineral soil is derived from marine sediments. Such C layers produce acid sulfate soil conditions and are classified as Sulfohemists. Their FCC class is OCc.

Traffic pans. FCC type and substrate type define the soil's capability to develop a traffic pan below the puddled layer. Traffic pans are a positive attribute of rice-growing soils because they facilitate wetland preparation and decrease percolation losses. Traffic pans develop more readily in L soils than in either S or C soils, with the exception of Lx soils, which are mainly classified as Andepts (9, 25). Similar

Table 5. Percentage distribution of 410 lowland rice soils in tropical Asia according to textural class.[a]

Country	Distribution (%)		
	Sandy	Loamy	Clayey
Bangladesh	6	65	29
India	4	41	55
Indonesia	2	28	70
Malaysia	6	23	71
Philippines	4	33	63
Sri Lanka	30	40	26
Thailand	25	29	45

[a] Adapted from Moormann and van Breemen (26), based on data by Kawaguchi and Kyuma (23).

physical properties are often encountered in soils with an abrupt clay increase in the subsoil (SC or LC), which are often classified as Planosols in the FAO Legend.

Puddling. FCC classes also help identify the topsoil's relative ease of puddling as well as the regeneration of the original structure upon drying and subsequent land preparation. In C soils (except for Ci), it is easier to break down the structural aggregates during wetland preparation, particularly in Cv or Cb soils that have smectitic mineralogy (31). Ci and Lx soils are most difficult to puddle because of the very strong degree of aggregation of Oxisols and oxic groups of Ultisols and of Alfisols (Ci soils) and Andisols (Lx soils). O soils are also very difficult to puddle, as are S soils.

The degree of structure regeneration upon drying and subsequent land preparation is inversely related to the ease of puddling. Cv and Cb soils regain their original structure with more difficulty than L soils (31). The difficulty in puddling Ci, Lx, S, and O soils usually results in incomplete aggregate destruction, which permits a rapid return to their original condition. C soils without the d modifier, indicative of a strong dry season, are more difficult to regenerate than Cd soils. The difficulties in rotating rice with other crops in puddled fields can, therefore, be interpreted from FCC terminology.

Condition modifiers

Poor drainage. The g parameter defines the aquic soil moisture regime, which is usually favorable to rice because higher yields are generally obtained in flooded anaerobic soils than in aerobic soils (24, 29). Anaerobic conditions are less difficult to maintain in g than in well-drained (non-g) soils.

Prolonged flooding. One exception to the advantages of g soils is that continuously submerged soils are definitely less productive than periodically drained soils (6 cited in 25). The main reason has now been identified as Zn deficiency (22). The g* (pergleyic) modifier proposed in this paper identifies such soils by the absence of brownish or reddish mottles, indicative of some Fe oxidation in the topsoil as well as in the subsoil.

Dry season. The d modifier identifies the opposite situation, where the subsoil is dry for at least 90 consecutive days in a year. This is a consequence of the dry season typical of ustic, aridic, or xeric soil moisture regimes. These gd soils probably represent the most common soil moisture pattern in rainfed rice. The seasonal alteration of flooding and drying probably results in denitrification losses and a lower efficiency of N utilization. For acid sulfate soils, van

Breemen and Pons indicate that the absence of a dry season favors rice production in such soils in comparison with those located in ustic climates because oxidation during the dry season decreases soil pH and may cause Al toxicity. Consequently, c soils present less severe management problems than dc soils. The presence of a d modifier also indicates the likelihood that only one rice crop can be grown per year without irrigation, unless early maturing varieties are used.

Low nutrient reserves. Kawaguchi and Kyuma (23), in their classic study of paddy soils of Southeast Asia, found "inherent potentiality" to be one of the four most important soil factors correlated with rice yields. Inherent potentiality is a function of the nature and amount of clay and base status. After examining Kawaguchi and Kyuma's results, it became apparent that the FCC k modifier quantitatively defines soils with low inherent potentiality as those having less than 10% weatherable minerals in the sand and silt fractions within 50 cm of the soil surface. Most soils classified by Kawaguchi and Kyuma as having low inherent potentiality possess the k parameter, while those considered as having high inherent potentiality do not have the k parameter. Since k soils are low in weatherable minerals, they usually fall in the siliceous, kaolinitic, or halloysitic mineralogical families, but not in the richer mixed, illitic, chloritic, or smectitic families.

Moormann and van Breemen's (26) discussions on mineralogy can, therefore, be rephrased in FCC terminology. The absence of weatherable minerals in old basaltic k soils from Vietnam reflects their lower productivity in relation to soils derived from more recent basaltic deposits, which do not have the k modifier. In Southern Luzon, Philippines, continuous cropping of upland rice and other crops is possible in the Mollisols, Andisols and Tropepts of Batangas Province but not in the nearby Udults of Quezon Province, where shifting cultivation is still dominant. According to Moormann and van Breemen (26), these soils have similar topography, moisture regime, and clay content. Udults have the k modifier, while the three soil groups from Batangas do not.

Low cation exchange capacity. The e modifier defines soils with effective CEC values of less than 4 meq/100 g soil, which indicates the soil's limited ability to retain nutrients. Loamy and clayey soils with this modifier (Le and Ce) usually have low activity clays. Although the ability to retain nutrients against leaching is less critical in puddled g soils than in typical non-g soils, the e modifier is indicative of a low buffering capacity, which makes the flooded soils more susceptible to changes caused by external factors.

One example is Fe toxicity caused by Fe-rich interflow from adjacent uplands (38). Such soils are often poorly buffered and often have both the e and the k modifiers. Examples are Sgek or Lgek soils from inland valleys of the wet zone of Sri Lanka classified as Aquents (26).

Another condition related to the e modifier is Si deficiency in the acid sandy soils of Japan and Korea. Such soils often have the gea modifiers.

Ferrolyzed or degraded paddy soils are usually Aquults that can be classified as SLgkea or LCgkea, with a coarser topsoil than subsoil texture, few weatherable minerals, low cation exchange capacity, and pH of 4-5. The low buffering capacity of such soils may result in H_2S toxicity when $(NH_4)_2SO_4$ or other S-containing fertilizers are applied.

Soils with the e modifier may have additional management limitations related to N management because of somewhat greater percolation. They are also more susceptible to nutrient imbalances, particularly among K, Ca, and Mg. Fertilizer management requirements are higher in e than in non-e soils.

Soil reaction. Soil acidity in the FCC system is accounted for by three mutually exclusive modifiers: a when the pH is less than 5.0, h (acid but not Al toxic) when the pH is between 5.0 and 6.0, and b (basic reaction) when the pH is above 7.3 The absence of a, h, or b modifiers, therefore, indicates a pH between 6.0 and 7.3, which is considered the optimum range. All these values refer to pH measured in 1:1 H_2O under aerobic conditions. Although anaerobic pH is more directly relevant to rice growth, most characterization data give pH values in aerobic soil conditions.

The a modifier identifies soils with more than 60% Al saturation of the effective CEC within 50 cm of the soil surface. The aerobic pH of these soils is usually below 5.0. Aluminum is seldom a constraint under flooded conditions because pH increases to about 6.5-7 upon flooding and exchangeable Al precipitates in most soils. Aluminum toxicity is important in acid sulfate soils when they are drained, and affects the growth of direct-seeded rice in such soils before submergence takes place. The a modifier is frequently correlated with P deficiency. Soils with the a modifier should be tested for P. When the a occurs along with low exchange capacity and low nutrient reserves (aek), degraded paddy soils may be present.

An aerobic pH between 5.0 and 6.0 defined by the h modifier usually indicates a good chemical environment for rice growth, as the pH will rise to 6.5-7.0 with flooding. The absence of an a, h, or b modifier indicates an excellent pH range that is not likely to be altered by the chemical reduction of the soil.

Calcareous soils are identified by the b modifier defined by the presence of free $CaCO_3$ within 50 cm of the soil surface or an aerobic pH value greater than 7.3. The b modifier in wetland soils may be a result of calcareous parent materials, groundwater or irrigation water rich in $CaHCO_3$, mollusk shells deposited as a consequence of Ca-rich water, or massive lime applications in the case of some Chinese rice farmers.

Soils with a b modifier are usually prone to Fe and Zn deficiencies because of the low availability of these elements of high pH values. In most b soils flooding attenuates or eliminates Fe deficiency, but may accentuate Zn deficiencies. Not all b soils, however, will produce Fe and Zn deficiencies. Flooded rice grown in calcareous Aquolls along the coast of Peru with aerobic pH values of 8.3 produced yields above 10 t/ha with no fertilizer response other than N (32). Rice roots had typical Fe coatings, and no response to Zn was detected. Consequently, the b parameter can flag these deficiencies but does not guarantee their existence.

Soils with a b modifier require more careful N management because of their propensity to volatilize NH_3 from surface-applied urea. The efficiency of N utilization may be enhanced by incorporating N fertilizers into the puddled soil.

Interpretation of the modifiers for vertic properties (v), salinity (s), alkalinity (n), acid sulfate soils (c), gravel (*), and steep slopes (%) are straightforward and are shown in Table 4.

Anthropic wetlands

Many soils with sufficient water-holding capacity but lacking an aquic soil moisture regime are converted into artificial wetlands through irrigation and terracing. Such soils may develop the diagnostic criteria for an aquic moisture regime, and, if they do, they have the g modifier in the FCC system. Others develop only surface gley properties underlain by subsoil without gley colors or mottling. The epiaquic moisture regime requires consideration from the taxonomic viewpoint. From the agronomic viewpoint, one important factor is that many of these soils are acid and thus carry FCC modifiers indicative of high P fixation (i, x), low CEC (e), and Al toxicity (a), which are infrequent in naturally wet soils. Many terraced fields are classified as Oxisols and oxic subgroups of Ultisols, Alfisols, and Dystropepts. Such terraces are common in Indonesia, the Philippines, Sri Lanka, and other countries. Paddy rice is also grown on Andepts, which generally do not have an aquic soil moisture regime. Terraces constructed from materials carried from other

locations are classified as Entisols, but their fertility often reflects the soils from which the materials originated. Two of the most common groups are described below.

Oxic soils. The i parameter defines high P fixation by Fe as a free Fe_2O_3-clay ratio greater than 0.15 with more than 35% clay in the topsoil or hues redder than 7.5 YR and a granular structure. This parameter identifies Oxisols and oxic groups or subgroups of Ultisols, Dystropepts, and Alfisols. Soils with an i parameter are extremely difficult to puddle and can cause severe Fe toxicity when flooded (27). These two factors have prevented the development of flooded rice production in the level Oxisols of the Colombian Llanos. Ci soils located in upland positions can cause Fe toxicity to adjacent lowlands because of the Fe-rich interflow during the rainy season. Although the i parameter was originally designed to indicate high P fixation capacity, its interpretation for aquic soils also has different connotations in terms of Fe toxicity, resistance to puddling, and quick regeneration of the granulated structure upon drying.

Andepts. The x parameter defines those soils derived from volcanic ash that are sufficiently developed to have allophane as the dominant mineral. Such soils, when grown to flooded rice, demonstrate high nutrient reserves but often acute N and P deficiencies as well as P fixation. The difficulties in puddling are less than in i soils, but their ability to recover the original structure upon drying permits crop rotation. Kawaguchi and Kyuma (23) ranked volcanic (Lx) soils from Luzon and Java as the most productive among the 410 soils sampled from tropical Asia.

FCC CLASSIFICATION OF PROBLEM SOILS

Tentative FCC classes for rice problem soils are presented in Table 6. FCC modifiers that identify nutritional disorders of the rice plant are proposed in Table 7. A translation of common disorder names into FCC classes is shown in Table 8. These three tables are

Table 6. Identification of problem soils for rice production by FCC classes.

Problem soil	FCC class[a]
Acid sulfate soils	Cc
Peats (deep)	O
Peats (shallow)	OC, OL, OS
Saline soils	s
Alkali soils	n
Skeletal soils	SL", LC", SR or LR

[a] In addition, all carry the g modifier.

Table 7. Identification of probable nutritional disorders of the rice plant under aquic soil moisture regimes by FCC criteria.

Nutritional disorder	FCC class[a]
Deficiencies	
Fe	**b**
Zn	**g*, b, O**
K	**k, kb, O, S**
P	**a, h, i, x, v, O**
Cu	**O, g'**
Si	**keh, ka**
S	**x, i, S**
Mo	**O**
B>	**a**
Toxicities	
Salinity	**s**
Alkalinity	**n**
Salinity and alkalinity	**sn**
Fe toxicity	**Ci, ek** lowlands with interflow from **Ci** uplands, **c**
H_2S toxicity	**SLak, CLak** (with S fertilization), **C**
Organic substances	**O, Ske** low in organic matter
Fe toxicity + P deficiency + Al toxicity	**c** (acid sulfate soils)
I toxicity	none, associated with **x** soils with I content
B toxicity	**n, s,** but depends largely on B content of irrigation water

[a] In addition, all have the **g** modifier.

Table 8. FCC classes in which commonly named nutritional disorders occur.

Nutritional disorder	FCC classes
Bronzing	**Ci, ek** lowlands with interflow from **Ci** soils.
Anaranjamiento	**Ci**
Akiochi	**SLka** (with S fertilization)
Akagare type I	**SLek** or **LCek** with adjacent **Ci** uplands
Akagare type II	**b, g*b**
Akagare type III	**x** with high iodine contents
Khaira	
Taya-taya	**b, g*b**
Hadda	

presented as working hypotheses subject to modifications by people more experienced in these disorders than the authors of this paper.

GEOGRAPHICAL DISTRIBUTION OF SOIL CONSTRAINTS IN WETLAND SOILS

A gross approximation of the importance of the above-mentioned constraints can be gleaned by interpreting the FAO-UNESCO Soil map of the world into FCC units. Data from the FAO Soil map sheets for South Asia,

Southeast Asia, Africa, Mexico-Central America, and South America (8, 9, 10, 13, 15) and the FAO Agro-ecological Zone studies for these regions (14, 16, 17) have been kindly supplied to North Carolina State University's Tropical Soils Research Program by FAO on computer disks. Mapping units and climatic data were translated into FCC units by methods described elsewhere (33). We asked the computer to provide us the areal extent of FCC classes for soils having the g modifier. The results are summarized in Tables 9 and 10.

Table 9. Extent of FCC textural classes in soils with aquic moisture regime in three developing regions. Based on the *FAO World soil map* at the scale of 1:5 million.

FCC class (all g soils)	Extent of area				
	South and Southeast Asia (ha × 10^6)	Africa (ha × 10^6)	Latin America (ha × 10^6)	Total (ha × 10^6)	%
C (clayey)	44	54	154	253	45
L (loamy)	27	55	36	117	21
LC (loamy over clayey)	17	25	25	67	12
S (sandy)	4	46	6	55	10
O, OC (peats)	23	12	9	45	8
SL (sandy over loamy)	6	8	–	14	3
SC (sandy over clayey)	–	3	1	4	–
Total	121	203	231	555	100

Table 10. Extent of FCC condition modifiers in soils with aauic soil moisture regimes of three developing retions of the world. Based on FAO World Soil Map of the scale of 1:5 million.

FCC class (all g soils)	Distribution				
	South and Southeast Asia (ha × 10^6)	Africa (ha × 10^6)	Latin America (ha × 10^6)	Total (ha × 10^6)	%
d (Dry season)	72	139	139	350	63
h (Moderately acid)	42	72	50	164	30
– (No modifier)	12	20	48	81	15
s (Salinity)	11	11	15	37	7
a (Al toxicity)	14	2	6	22	4
k (Low nutrient reserves)	14	2	3	19	3
c (Acid sulfate soils)	6	5	2	13	2
ak (Ferrolyzed)	11	2	–	13	2
b (Calcareous)	2	3	1	6	1
n (Sodic)	1	3	–	4	1
e (Low effective CEC)	1	1	1	3	–
/ (Gravel)	–	1	–	1	–
C[a] (Structure regeneration)	11	19	62	91	16
L, LC[b] (Traffic pans)	44	80	61	184	33

[a]Cg soils that do not have d, k, or i modifiers. [b]L soils that do not have an x modifier.

The results presented in these tables have the following limitations:

1. The small map scale (1:5 million) is insufficient for local validity. For example, the Central Plain of Luzon consists of only six mapping units at this scale.
2. Only soils that are naturally poorly drained are included; anthropic wetlands are, therefore, excluded and so are irrigated soils without an aquic soil moisture regime.
3. It was not possible to separate shallow from deep organic soils, nor to identify areas with prolonged submergence or those subject to Fe-rich interflow from adjacent uplands.

Data in Tables 9 and 10 indicate that many soils with aquic soil moisture regimes in the tropics are well suited for rice production. The preferred clayey and loamy textural classes are found in 78% of the 555 million ha of g soils of tropical Asia, Africa, and Latin America. Only 21% of the wetlands have the more difficult sandy and organic type and substrata types.

The most extensive condition modifier is the presence of a dry season in 63% of the wetlands area (Table 10). The next most extensive is moderate acidity. This is really not a constraint to flooded rice production and thus can be considered together with areas having no major limitations for rice, indicated by lacking FCC condition modifiers other than g. About 25% of the tropical wetlands therefore, have major chemical limitations to rice production other than N deficiency. About one-third of the wetlands have the potential for a traffic pan formation, which is a positive attribute for rice production.

The next major constraint is the difficulty in regenerating the soil's original structure, which is destroyed by puddling. About 16% of the tropical wetlands have clayey montmorillonitic soils and no dry season. We presume these soils would have the greatest difficulty in structure regeneration.

It is apparent from Table 10 that the most extensive constraints to rice production in wetland soils are physical rather than chemical. The most extensive chemical constraint is soil salinity, but it covers only 7% of the wetlands. Other identifiable constraints such as Al toxicity, low nutrient reserves, acid sulfate, calcareous, sodic, low CEC, gravelly, or ferrolyzed soils cover a small proportion of the total. These tables help us understand how it is possible to feed rice to so many people and why rice is the number one food crop in the tropics.

Although the individual percentages may be small, wetland soils with severe chemical constraints are increasingly important because the productive potential of many of the better soils has been approximated and

Table 11. Main soil constraints or attributes in aquic moisture regimes quantifiable by the FCC system. Based on *FAO World soil map* at the scale of 1:5 million.

Constraint or attribute	FCC class (all g soils)	Distribution (%)			
		South and Southeast Asia	Africa	Latin America	Total
Dry season	d	60	69	60	63
No major limitations[a]	h, none	16	21	34	25
Traffic pan	L, LC	36	39	26	33
Difficult to puddle	S, O, Ci, Lx, Ck	27	34	7	22
Structure regeneration	C (not d, k, i)	9	9	27	16
Sandy topsoils	S, SL, SC	8	28	3	14
Organic soils	O, OC	19	16	4	8
Saline soils	s	9	5	7	7
Strongly acid[b]	a	12	1	3	4
Low nutrient reserves	k	11	1	1	3
Acid sulfate soils[b]	c	5	2	1	2
Ferrolyzed soils	SLak, LCak	9	1	–	2
Fe and Zn deficiency, NH_3 volatilization	b	2	1	–	1
Sodic soils	n	1	1	–	1
High leaching potential	e	1	–	–	–
Gravel	/	–	1	–	–

[a]Other than N deficiency. [b]P deficiency likely, Al toxicity if aerobic.

because there is need to expand rice production into marginal lands. Those marginal lands include 37 million ha of saline soils, 22 million ha of strongly acid soils, 19 million ha of soils with low nutrient reserves, 13 million ha of acid sulfate soils, another 13 million ha of ferrolyzed soils, and 45 million ha of organic soils (Table 10).

Table 11 indicates the percentage distribution of the main constraints by region. The potential for increasing the world's rice production area lies largely in Latin America and Africa, both of which appear to have less severe constraints to rice production than South and Southeast Asia. Since most of the wetlands in Africa and Latin America are not used for rice, the world appears to have ample wetland soil resources to meet rice demands for many years to come.

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ECOLOGY OF FLOODED RICE FIELDS

I. WATANABE and P. A. ROGER

Some of the biological concepts and findings relevant to the study of the flooded rice field as an ecosystem are reviewed. The flooded rice field is an artificial ecosystem characterized by extreme instability resulting from frequent destruction of the environment by farming practices. This inhibits the successive development toward marsh and has made monocropping of rice possible for centuries. However, the instability of the ecosystem during the crop has discouraged quantitative approaches by limnologists and ecologists. Therefore topics dealt with here are not supported by a large volume of data. Studies conducted in freshwater ecosystems (lakes, ponds) may help us understand flooded rice fields, but extrapolation is not possible. The floodwater has been neglected in most agronomic, chemical, and soil studies. Its effect on fertility and other properties of flooded rice soils is stressed. Major biological activities in floodwater and soil, recycling of nutrients, and interactions between floodwater and soil are reviewed.

In 1942, Shioiri (25), in his lecture on the soil chemistry of paddy soils, mentioned that "Material transformation in paddy rice fields during flooding resembles that in lake and swampy land." When describing N losses by denitrification, he discussed mechanisms characterizing wetland rice fields. These mechanisms can be summarized as follows: 1) differentiation into oxidized and reduced layers after flooding of the oxidized layer, 2) destruction of this differentiation during the nonrice-growing period because of drying and plowing, 3) provision of C and N to soil surface by autotrophic plants during flooding and chemical transformation by these plants, and 4) oxidation of NH_3 in the oxidized layer and subsequent reduction to gaseous N, leading to N losses by denitrification.

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Since then, the fourth point has received more attention from researchers, whereas the third one, which we want to emphasize in this paper, has been relatively neglected with the exception of N-fixation by blue-green algae. A large volume of information on flooded rice soils has been published and reviewed (19, 24, 31, 34). Reviews have generally dealt with the chemistry, biochemistry, and microbiology of the flooded anaerobic soil, not with the chemistry and the ecology of the floodwater.

Some emphasis was given to floodwater microbiology in Watanabe and Furusaka's review (31). However, consideration of floodwater and underlying soil as an ecological entity has not been sufficient. On the other hand, limnologists and ecologists have studied aquatic and wetland ecosystems extensively. Their results assist the understanding of the ecology of flooded rice fields, but the studies should be extrapolated to rice fields, with the researchers keeping in mind that the rice field ecosystem differs from a lake on two major points: 1) the high frequency of mechanical disturbances and 2) the general oxidized condition of the shallow floodwater, which does not develop a reduced hypolimnion as in a lake.

This paper presents some of our views on the flooded rice field as an ecosystem where energy flow, input, output, recycling of materials, the interrelationship of trophism, structure of the communities, and their habitats have to be investigated. In flooded rice fields, the depth of the floodwater varies from a few centimetres to more than 1 metre. This review deals primarily with irrigated fields where the floodwater level is maintained up to about 10 cm.

GENERAL CHARACTERISTICS OF THE ECOSYSTEM

Instability and stability

A flooded rice field is an artificial ecosystem that is very frequently disturbed by farming practices -- weeding, tillage, irrigation, fertilization, cropping, plant protection measures, etc. -- and natural phenomena like rainfall, which result in extreme instability and fluctuations on a short time scale (crop cycle) but in stability on a long time scale. Despite the eutrophic nature of the rice field, frequent destruction of the environmental conditions by human activities inhibits its successional development toward a marsh. Thus, monocropping of rice has been possible for centuries. However, the extreme instability of the ecosystem during the crop cycle has excluded scientific and quantitative approaches by pure limnologists.

Structure of the system

The flooded soil-rice ecosystem consists of the following five major subsystems:

1. floodwater,
2. surface oxidized (or oxic) layer,
3. reduced (or anoxic) puddled layer,
4. subsoil (oxidized in well-drained condition, reduced when water table is high), and
5. the rice plant and its phyllosphere (dipped in water) and rhizosphere.

Although these subsystems can be differentiated macroscopically, they are more or less continuous. In particular, the floodwater and surface soil can be treated as a continuous system. For example, some algae become benthic at night and floating during daytime, and some epipelic organisms like chironomids migrate between the two.

When discussing energy flow and material exchange, the interaction among the subsystems is a key issue that will be stressed in this paper.

In each subsystem there are lower level subsystems in which the biotic communities develop more or less separately. For example, floodwater benthic association can be divided into 1) epibiose, which grows on the light exposed surface; 2) mesobiose, which grows on the shaded banks or within rice stubbles; and 3) hypobiose, which grows under the epibiose. In anaerobic soil, some pseudomonads live in the interstitial water (soil solution), most cellulose-decomposing flora on plant debris, and some sulfate-reducing bacteria selectively within soil aggregates (31).

Transformation of nutrient salts in flooded rice soils has been a major topic of edaphological studies of these soils. Attention has been paid largely to the transformations in soil (in a narrow sense). Recently, transformations of N have been studied in floodwater considered as the site of loss of the surface-applied N fertilizer (3). But transformation and recycling of N within soil or floodwater and between the two have been relatively neglected. Information on P, S, and other elements is more limited.

FLOODWATER AND SOIL-WATER INTERFACE

In irrigated rice fields, the floodwater is an oxic-photic environment. The transition between the floodwater and the anoxic-aphotic reduced soil is made by the oxidized soil-water layer. The floodwater and the oxidized layer constitute a continuous ecosystem in which four major mechanisms related to soil fertility take place:

1. biological N-fixation,
2. N losses by volatilization of NH_3, in relation to the photosynthetic activity of the biomass, and by the nitrification-denitrification process,
3. trapping and recycling by the photosynthetic biomass of C and mineral salts released from the soil and fertilizers, and
4. transport of nutrients from the soil to the water by the phytoplankton and the primary consumers.

The intensity of these reactions is directly related to the properties of the floodwater and the activity of the biomass.

Chemistry of the floodwater

The chemical status of standing water depends primarily on that of the irrigation water and the soil. However, its composition varies much during the crop cycle and within a field plot in relation to

1. fertilizer application;
2. mechanical disturbances of the soil, causing dispersion of soil particles in the water;
3. nature and biomass of the aquatic communities;
4. dilution by rainfall and irrigation water;
5. adsorption to surface soils; and
6. rice growth.

Diurnal variations occur mainly in relation to the activity of the photosynthetic biomass and may cause large variations in dissolved O_2 and CO_2 and in pH. As the crop grows, diurnal variations become less marked due to shading by the canopy.

Standing biomass and productivity of the floodwater

The major components of the total biomass in the standing water are: bacteria, phytoplankton, aquatic macrophytes (mainly submerged and floating weeds), zooplankton, and aquatic invertebrates.

The only available quantitative evaluation of the bacterial biomass in the floodwater of a rice field (2) seems to indicate a low contribution of bacteria (0.016 mg/litre). However, bacterial blooms were observed by the authors in a Histosol in the Philippines.

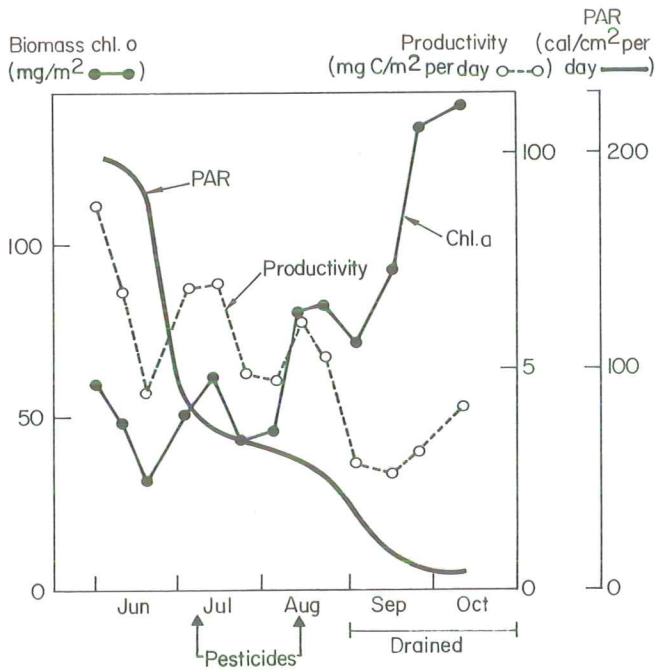
Total algal biomass evaluations range from a few kilograms per hectare to 23 t fresh weight (FW) or to 500 kg dry weight (DW) (21). The N-fixing algal biomass evaluations have the same range (20). However, the significance of these evaluations is of little value without the record of either water or ash content, or both, which vary within very large limits (9). Recent evaluations on artificially produced blue-green algae blooms indicated standing biomass of

N-fixing blue-green algae culminating at 150-250 kg DW/ha on an ash-free basis, corresponding to 10-20 kg N/ha (9). Reported data on N-fixation related to blue-green algae varied from a few to 80 kg/ha and averaged 27 kg/ha per crop (20).

The potential productivity of aquatic weeds seems higher than that of algae. Reported standing crops average 500 kg DW/ha but some very high values around 10-25 t DW/ha have been reported (21).

The zooplankton population can reach densities of 10-20,000/m^2, corresponding to biomasses of up to a few kg DW/ha (5, 13). Similarly, invertebrate populations living at the soil-water interface, such as chyronomid larvae and tubificids, may reach densities of 20,000/m^2, corresponding to a biomass of a few kg DW/ha (6, 4). Snails may develop biomasses as large as 1,000 kg FW/ha (20).

Some data on the productivity of the floodwater are available. In the Philippines, Saito and Watanabe (22) reported a net primary production of the flood community of 50-60 g C/m^2 in 90 days. In Japan, Yamagishi et al (33) reported a gross production of 71 g C/m^2 in 144 days. The relation among productivity, biomass, and photosynthetic active variation in the floodwater during a crop cycle in Japan is shown in Figure 1. Both values were of the same order as those encountered in eutrophic lakes.



1. Changes in photosynthetic active radiation (PAR), biomass, and productivity of floodwater in a rice crop cycle (adapted from [33]).

Floral and faunal changes during the crop cycle

The available information on the quantitative and qualitative variations of the algal flora has been summarized by Roger and Kulasooriya (20). Total algal biomass can reach a peak anytime during the crop cycle. Its occurrence is related mainly to fertilizer application and climatic conditions, especially light availability, as affected by the season and the rice canopy. Algal successions are governed by a large set of factors, including climatic, trophic, biotic, and soil factors, as well as agronomic practices. Factors that lead to the development of a N-fixing algal bloom are still poorly understood and may include N depletion of the floodwater, P availability, low CO_2 concentration due to alkaline reaction, low grazer populations or presence of algal populations resistant to grazing, and optimal temperature and light intensities.

Little is known about faunal changes during the crop cycle. In a study of plankton successions in a rice field in Japan, Kurasawa (13) observed a peak of phytoplankton 1 week after transplanting, followed 2 weeks later by a peak of zooplankton. Decline of the zooplankton started 6 weeks later, before that of the phytoplankton, indicating that some algae were resistant to grazing. Population changes of aquatic invertebrates were studied by Lim (15) in pesticide (carbofuran, carbaryl, endosulfan)-treated and -nontreated fields in Malaysia. Nematodes, hemipterans, and dipterans dominated in nontreated plots whereas ostracods, dipterans, and conchostracans dominated in treated plots. Temporal changes, community structures, and populations were affected not only by pesticides but by cultural practices, fertilization, and the development of aquatic macrophytes. The overall invertebrate population was higher in pesticide-treated plots, mainly because of the rapid recovery of ostracods. But the effects of pesticides may differ with their selectivity.

Recycling of nutrients

Carbon and nitrogen. The photosynthetic biomass assimilates CO_2 (and CH_4 after it is oxidized to CO_2) evolved from the soil and returns it as algal cells and aquatic weeds, therefore preventing organic matter losses in the form of CO_2 (7). A similar role in preventing, to a certain extent, losses of NH_3 dissolved in the floodwater is also possible. In lysimeter or pot experiments, Shioiri and Mitsui (26) and Vlek and Craswell (28) recovered 10-30% of N added as urea or $(NH_4)_2SO_4$ in the algal biomass.

Phosphorus. Most of the soluble phosphate applied to flooded soils is fixed on the solid phase of the soil. Very little remains in the floodwater. Transfer

of P from soil to standing water involves three major mechanisms: 1) mechanical disturbances of the soil, 2) diffusion from the soil, and 3) activity of the plankton and the fauna.

When the soil is disturbed, the solid phase and soil solution are mixed with standing water, and P transfers from soil. This happens because of land preparation, cultural practices (weeding, pesticide and fertilizer applications, etc.), and heavy rains. Short-term algal blooms were observed following disturbance of sediments in experimental ponds (1). In the IRRI farm we have occasionally observed the development of blooms after a mechanical disturbance of the soil.

A second possible mechanism is diffusion from the soil to the water. Knowledge of that mechanism stems from studies conducted in lakes and estuarine environments. Orthophosphate may be adsorbed onto or disorbed from sediments, depending on the relative amount of P in solution, or sorbed onto the solid phase. The rate of removal of interstitial P from the sediment surface layers is determined by

- the degree to which the sediment acts as a trap or a buffer, with the concentration of P in the sediment fluctuating in response to changes in P concentration in the water;
- the porosity of the mud; and
- the circulation of water over the mud surface (32).

The role of the oxidized zone in controlling regeneration of P has not been fully elucidated. Mortimer (17), who evaluated exchange of nutrients between the sediment and the water, concluded that as long as the O_2 concentration at the sediment surface is greater than 2 µg/litre, sediment release of nutrients is nil. It has also been suggested that the oxidized layer acts as a barrier to the exchange of P because of the presence of Fe^{3+}. However, in rice fields, this layer is frequently thin, unconsolidated, with a high water content.

A third mechanism by which P may travel from soil to floodwater is the active transport by living organisms such as 1) bottom-feeding organisms like ostracods, 2) tubificids that move back and forth from the soil to the floodwater, and 3) phytoplankton. The vertical movement of phytoplankton, in relation to nycthemeral cycles, permits algae, when benthic, to absorb nutrients from the soil some of which are released when they float during daytime. Phosphorus from the sediments is readily available to algae growing in intimate contact because of 1) the existence of a large pool of highly mobile phosphate bound to the solid phase of sediments and in equilibrium with a lower concentration of P in solution, and 2) the

production of phosphate-solubilizing substances by algae. Wada (Mitsubishi Life Science Institute, pers. comm.) pointed out that P uptake by the aquatic community in polluted paddy fields is proportional to P concentration at 1-2 x 10^{-6} mol/litre (30-60 ppb).

Release of nutrients by the biomass. The mechanisms and extent of release of nutrients accumulated in algae and aquatic weeds have been reviewed by Roger and Watanabe (21) and can be summarized as follows:

- Living aquatic plants continuously excrete appreciable amounts of dissolved organic matter, including soluble nutrients. This excretion is particularly pronounced in senescent plants and, undoubtedly, the largest proportion of nutrients tied up in plant tissues is released after death.
- Algae and aquatic weeds show great variations in their decomposition rate (and in the conversion of plant N to mineral N by soil microorganisms).
- The extent of the decomposition and the consequent regeneration of N and P into the water in a soluble form are similar in aerated and non-aerated conditions.
- The relative regeneration rate of P from algae and submerged macrophytes is higher than that of N.
- When photosynthetic biomass decomposes in the floodwater, the nutrient regeneration, together with other parameters, can markedly affect the dynamic seasonal succession of the phytoplankton, but availability of the nutrients to the rice plant is poor.

REDUCED SOIL

The reduced-soil subsystem has most frequently been studied as an isolated one, and the presence of overlying floodwater and the material exchange with floodwater have been neglected. Here, the interactions between the two subsystems are emphasized.

Organic matter input

In spite of the importance of organic matter supply in supporting and maintaining microbial growth, the quantitative data on flooded rice soils are still very presumptive. Possible sources of organic matter are roots and stubble remaining after harvest, material released from roots during rice growth, weeds (macrophytoplankton), and algae (microphytoplankton).

No quantitative data about organic and inorganic C released from wetland rice roots are available. Sauerbeck and Johnen (23) reported measurements of C release from roots of wheat grown in a ^{14}C atmosphere from

seedling stage to maturity. They presumed that about 20% of the CO_2 produced by the roots came from root respiration and the remainder from decomposition. Carbon decomposed during root growth plus fractions of root-^{14}C remaining after the roots' separation from the soil were designated as "rhizodeposition." The researchers stated that this rhizodeposition amounted to 3-4 times more than that found as root residue at harvest time. By adding this "rhizodeposition" to the table presented by Saito and Watanabe (22), the total amount of organic C input into a rice soil was estimated at 1.7-2.2 t C/ha in 90 days (Table 1).

Kimura et al (11) approached the dynamics of organic matter supply from another direction. Organic matter is largely supplied as large organic debris. As it decomposes its size decreases (30), and 30% of total organic matter exists as organic debris larger than 37 μm. Kimura et al (11) studied seasonal changes in the amount of organic debris larger than 1 mm in a Japanese soil. They observed a first peak just before transplanting, followed by a gradual decrease during rice growth, and another increase just after harvest. The first peak corresponded to the incorporation of weeds grown during the winter fallow period, and the second to the incorporation of stubble and root. The increase in coarse organic debris was close to the amounts of winter weed biomass (0.6 t/ha in unfertilized plots and 3.3 t/ha in plots with organic manure) and stubble and roots (1 t/ha in unfertilized plots and 2 t/ha in plots with organic manure). Similar surveys were made in the Philippines (M. Kimura, pers. comm). There was no clear peak corresponding to the incorporation of organic matter. The amount of organic debris (1-2 mm) did not differ between tropical and temperate areas (1-2 t/ha). This fact may suggest a continuous supply of organic matter during the rice-growing cycle or a very rapid fragmentation of organic matter in the tropics.

Table 1. Estimation of organic carbon input into rice soil (after 22).

	Organic C input (t/ha per 90 days)	
	Fertilized	Unfertilized
Floodwater community	0.6	0.6
Rice straw and grain	3.9	2.3
Root	0.2	0.15
Input to soil		
Root	0.2	0.15
Floodwater	0.6	0.6
Stubble[a]	0.65	0.38
Rhizo-dep.[b]	0.8	0.6
Total	2.25	1.73

[a]One-sixth of rice grain and straw. [b]Four times root mass.

Microbiomass and its source with special reference to nitrogen transformation

Recently, the determination of microbial biomass and soil nutrient accumulation in and transfer through microbiomass have become popular topics in soil microbiology (10, 18). However, the application of these studies to flooded rice fields is still limited. Probably adenosine triphosphate (ATP) measurements used in sediment microbiology would be applicable. Kanazawa and Takai, during the Symposium on Biological Process of Soil Fertility (University of Reading, July 1983), reported an increase in the ATP content of soil during flooding. Jenkinson's chloroform fumigation method has an advantage for studying the turnover of nutrients through microbiomass. Inubushi and Watanabe (unpubl.) applied this method in water-saturated soil and found 90% killing of bacteria after a 12-h exposure to chloroform. Longer exposure seemed to mobilize the "stable soil N" fraction. The technique was applied to study of the dynamics of available N (N in the microbiomass plus N released from unfumigated soil) in Philippine soils (8; Inubushi and Watanabe, unpubl.), with the following major results:

- At the surface 0- to 1-cm layer, available N increased during rice growth. However, it did not increase in soil covered with black cloth, indicating that the increase was due to the photo-dependent community. The soil content in chlorophyll-like substances (A665) and available N were positively correlated. Wada et al (29) reported a similar close correlation of chlorophyll-like substances with the N-supplying capacity of soils. This means that the supply of organic matter by macrophytes and microphytes is important in flooded rice soils. In upland, grassland, and forest soils, fungi and bacteria are considered the major components of the microbial biomass. But in flooded soils, algae should not be overlooked as a component of microbial biomass.
- The total amount of available N per unit area did not differ between fallow and planted plots in spite of N uptake by rice.
- The ^{15}N-labeled fertilizer was rapidly incorporated into the available N pool. This newly immobilized N decomposes faster than the previously existing available N.
- After the NH_4^+ applied at transplanting was depleted by rice plant uptake (40 DAT), ^{15}N abundance in the N absorbed by the plants was close to that in the available N, but higher than that in the exchangeable NH_4^+-N. The N

absorbed by rice from 40 DAT to harvest was 1.5-3.3 times more than the available N content of the soil.

This finding suggests that the turnover of available N (probably microbial biomass) is faster in tropical paddy soils than in temperate ones, as shown in data from the Rothamsted Experiment Station (10). If all the N transferred to rice passed through the available N pool, ^{15}N should have been rapidly diluted, but ^{15}N abundance in the available N declined slightly in spite of a great turnover rate. This suggests that the ^{15}N originated from fertilizer must be recycled to build up the available N pool.

INTERACTION BETWEEN FLOODWATER AND REDUCED SOIL: ACTION OF TUBIFICIDS

The importance of underlying reduced soil in providing nutrients to a floodwater community was discussed above. Many factors like weeding, heavy rain, stepping in the fields, and actions of the fauna break the balance between floodwater and soil. Among them, tubificids are paid special attention because they are able to move back and forth between the reduced soil layer and the floodwater. Tubificids are benthic oligochaetes. Their role was reviewed by Fry (4) for aquatic sediments and by Kurihara (14) for flooded rice soils. The population in IRRI fields was about $10^4/m^2$ (6).

Tubificid activities are burrowing to search for feed, which results in aeration and mixing; and defecation and secretion, which results in the accumulation of fine particles on the soil surface and of NH_4.

Kikuchi and Kurihara (12) recognized tubificids as weed suppressors as they bury weed seeds and disturb early germination.

Marine and lake ecologists recognize tubificids as aerating agents, causing a deeper oxic layer and stimulating denitrification (4, 16). In paddy fields, the activities of tubificids however, result in the opposite effect, leading to a decrease of Eh, stimulation of NH_3 formation, and Fe reduction. The apparent difference may be explained by the irrigation effect discussed by Takai et al (27). In organic matter-rich soils like flooded rice soils, aeration and mixing stimulate organic matter decomposition. Because of stimulated organic matter decomposition, defecation, and destruction of the oxidized layer, organic matter, NH_4^+-N, Fe^{2+}, and PO_4^{-2} are released into the floodwater. The increase of these materials leads to the propagation of bacteria and aquatic flora and fauna, resulting in positive feedback that increases or maintains the tubificid population.

Grant and Seegers (unpubl.) obtained data showing that the presence of tubificids increased soil N uptake by rice plants and stimulated losses of N from buried algae cells. These results can be explained by the known roles of the tubificids.

CONCLUSION

A rice field is not a natural ecosystem, but is manipulated intentionally to improve soil fertility. This paper has presented some of the biological concepts and findings relevant to the study of the flooded rice field as an ecosystem. It attempts to illustrate how interactions between overlying floodwater and underlying soil take place and how these are important in the dynamics of the soil fertility of the wetland rice field. The interaction between rice plants and soil inhabitants in the rice rhizosphere is equally important, but because of limited space, this aspect is not presented here. Topics discussed in this paper are not supported by a large volume of data. Probably, a search for relevant data in reports from rice-growing countries will prove fruitful. But the ecology of the rice field as presented here seems to have received little attention and may offer many possibilities for further investigation.

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FERTILITY OF WETLAND SOILS

AVAILABILITY AND MANAGEMENT OF NITROGEN IN LOWLAND RICE IN RELATION TO SOIL CHARACTERISTICS

S. K. DE DATTA

Field studies with ^{15}N-labeled urea and $(NH_4)_2SO_4$ have shown that both N fertilizers are highly susceptible to different types of losses. Laboratory, greenhouse, and field experiments on NH_4^+ dynamics of lowland rice soils have greatly helped us understand N availability and fertility management based on soil characteristics, including clay mineralogy. To minimize gaseous losses, it is critical to study floodwater chemistry after fertilizer N application. Basal fertilizer N applied to standing water, with or without incorporation, is subject to volatilization loss. Employment of nitrification and urease inhibitors has generated information useful for further research. Among the alternative practices for increasing N efficiency, proper timing of N fertilizer and proper water management at the time of basal fertilizer application appeared most relevant at the farm level. Deep point placement, with or without applicators, appeared highly promising in most soils, including calcareous soil.

Total fertilizer use in the world for crop year 1981/82 was about 120 million t (8). The most widely used plant nutrient is N, and because of its advantages in production and savings in shipping and distribution costs, urea is the principal dry N source for upland crops (1) and for rice (4). However, field studies have shown that most N fertilizers are highly susceptible to different types of loss (20). Urea is often the least efficient of the NH_4^+-containing or NH_4^+-producing N sources (5). High losses and low N-use efficiency demand that factors responsible for such wastage of expensive input be studied. Modified urea products and improved application methods should deliver N to a crop in a more timely and effective

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manner and may be less susceptible to NH_3 volatilization, denitrification, leaching, and other modes of N loss (7).

This paper updates the information on some recent basic and applied studies relevant to increased fertilizer N efficiency in lowland rice soils.

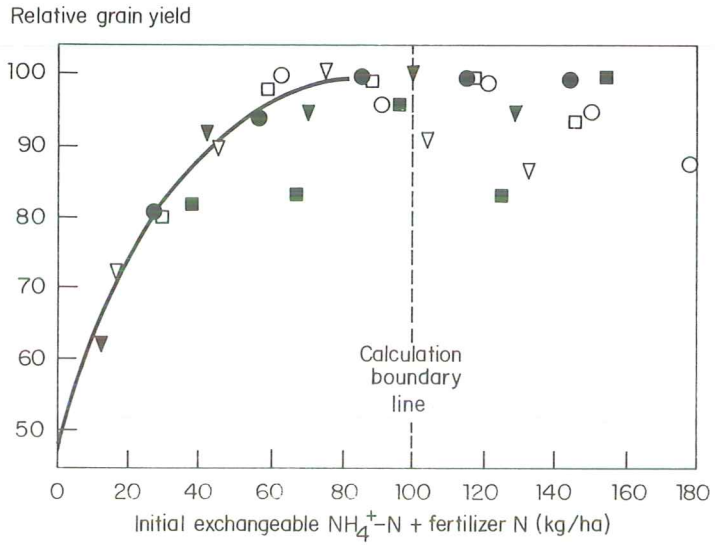
CURRENT RESEARCH ON NITROGEN DYNAMICS AND NITROGEN LOSS

Knowledge of the nature of soil N improves understanding of the dynamics of N transformations and its availability to the lowland rice plant. Furthermore, the magnitude and mechanisms of N loss should be identified for various soil and water regimes to facilitate development of suitable management practices for maximizing the use of fertilizer N within given soil, climate, and water regimes.

Nitrogen dynamics and soil fertility management

The predominant form of inorganic N in lowland soils is NH_4^+. Its concentration in the soil solution (intensity factor) is relatively smaller than that in the sorbed phase (capacity factor) in soils with high cation exchange capacity (CEC). Although the rice plant absorbs N from the soil in the form of NH_4^+ and NO_3^-, the contents of these ions in a soil sample frequently do not reflect the soils' N-supplying capacity throughout the growing period. The available N status in lowland soils is influenced by many chemical and biological processes. Patrick and Mahapatra (17) suggested that the determination of NH_4^+-N mineralized in anaerobic conditions may give a good estimate of the amount of N available to the lowland rice crop. Our recent results (21) show that if the initial exchangeable NH_4^+ and fertilizer N are plotted against relative grain yield, a Mitscherlich-type of crop response is obtained (Fig. 1), suggesting that the exchangeable NH_4^+ present in the soil at transplanting behaves like fertilizer N. The critical soil N level, which is the initial exchangeable soil NH_4^+ plus fertilizer N at which the optimum grain yield is obtained, differed for the various fertilizer application techniques.

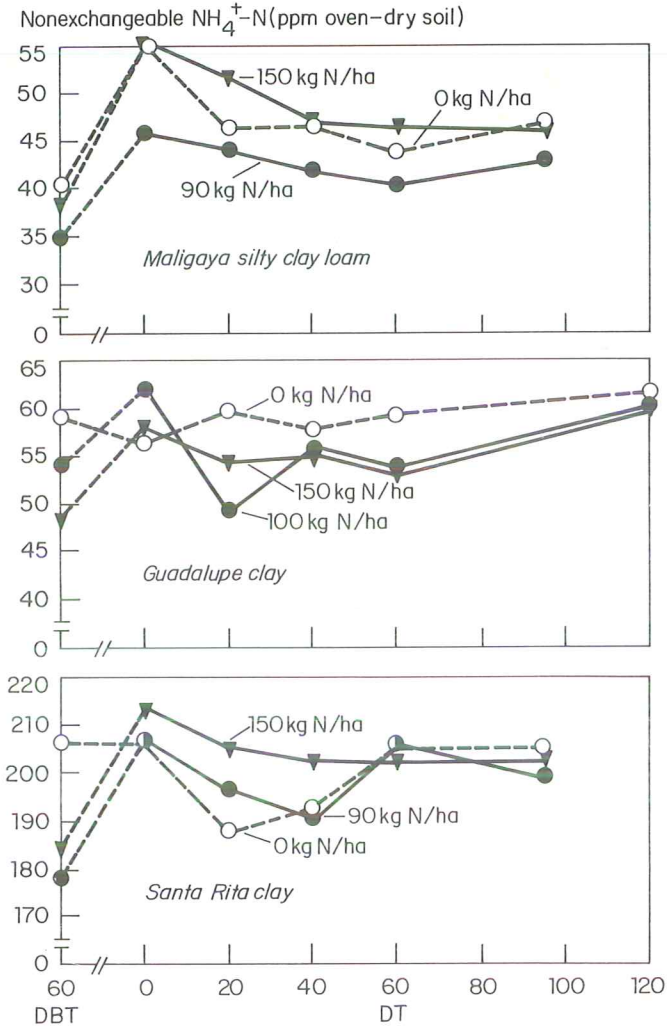
In subsequent studies (13) the release of nonexchangeable (fixed) NH_4^+ was examined in three representative rice soils in the Philippines. During the 1981 dry season, nonexchangeable NH_4^+ increased after fertilizer application in all three soils. The results (Fig. 2) suggest an apparent decrease of nonexchangeable NH_4^+ during the first 20 d after transplanting (DT) in all soils except the no-fertilizer plots in Guadalupe clay (Typic Pellusterts).



1. Relationship between initial exchangeable NH_4^+-N + fertilizer N rate and grain yield of rice grown on 6 soils using researchers' split application of prilled urea. 1980 wet season. (H. Schon, K. Mengel, and S. K. De Datta, IRRI-Justus Liebig University Cooperative Project, unpubl.)

Table 1 shows the amounts of nonexchangeable NH_4^+ present at the beginning and end of the experiment. In field incubation studies using ^{15}N tracer techniques, highly significant amounts of labeled nonexchangeable NH_4^+ were released from all three soils. In two (Maligaya and Guadalupe) of the three soils studied, both containing vermiculite, the total release of nonexchangeable NH_4^+ was higher than that of labeled nonexchangeable NH_4^+, showing that nonlabeled NH_4^+ was released as well. The results further suggest that the nonexchangeable labeled NH_4^+ was subsequently available to the crop. Fixation and release of NH_4^+ seemed to be more dependent on type of clay minerals (vermiculite) than on clay content. From these studies Keerthisinghe et al (12) concluded that a substantial amount of N taken up by a rice crop may originate from the nonexchangeable fraction of clay-bound NH_4^+. Subsequent studies also using ^{15}N tracer techniques (H. F. Schnier, K. Mengel, and S. K. De Datta, IRRI-Justus Liebig University Cooperative Project, unpubl.) delineated the N dynamics in the different soil fractions, i.e., exchangeable N, nonexchangeable (clay-fixed) N, and organic N.

The total amount of ^{15}N fertilizer recovered from the soil after 10 wk of incubation varied widely among soils. The ^{15}N recovery from Maligaya silty clay loam (Entic Pellusterts) from Central Luzon (located in the principal rice-growing region) was 60.3% (Fig. 3); that from other rice-growing soils



2. Content of nonexchangeable NH_4^+ in N-response experiments on 3 soils in the Philippines, 1981 dry season. DBT = days before transplanting, DT = days after transplanting. (G. Keerthisinghe, K. Mengel, and S. K. De Datta, IRRI-Justus Liebig University Cooperative Project, unpubl.)

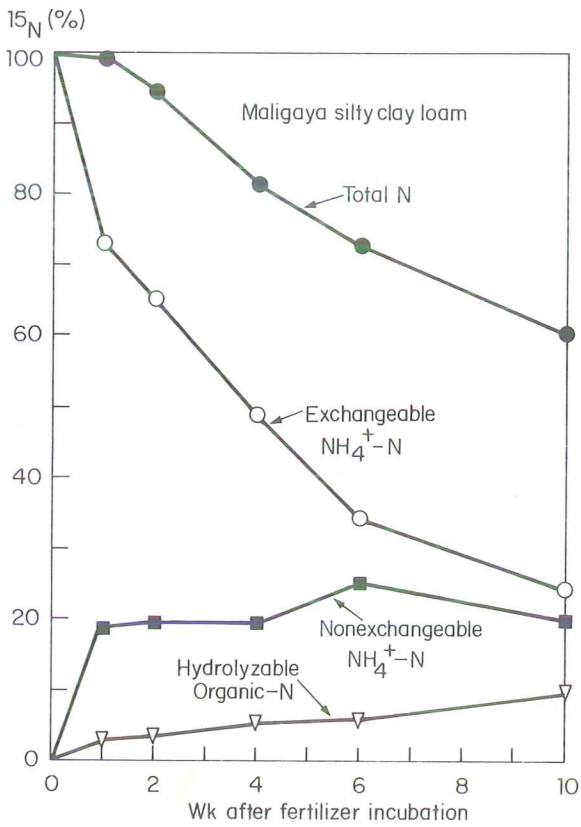
(Typic Pellusterts and Typic Pelluderts) varied between 38.5 and 59.2%. In a greenhouse experiment, the N uptake data from different soils were compared by plotting the highest uptake values of one. Nitrogen uptake values from other soils were plotted relative to the highest value of one (Fig. 4). The lowest total and fertilizer N uptake was from Maligaya soil (H. F. Schnier, K. Mengel, and S. K. De Datta, unpubl.)

These basic studies on the NH_4^+ dynamics of lowland rice soils have greatly helped us understand N availability and fertility management based on soil characteristics, including clay mineralogy.

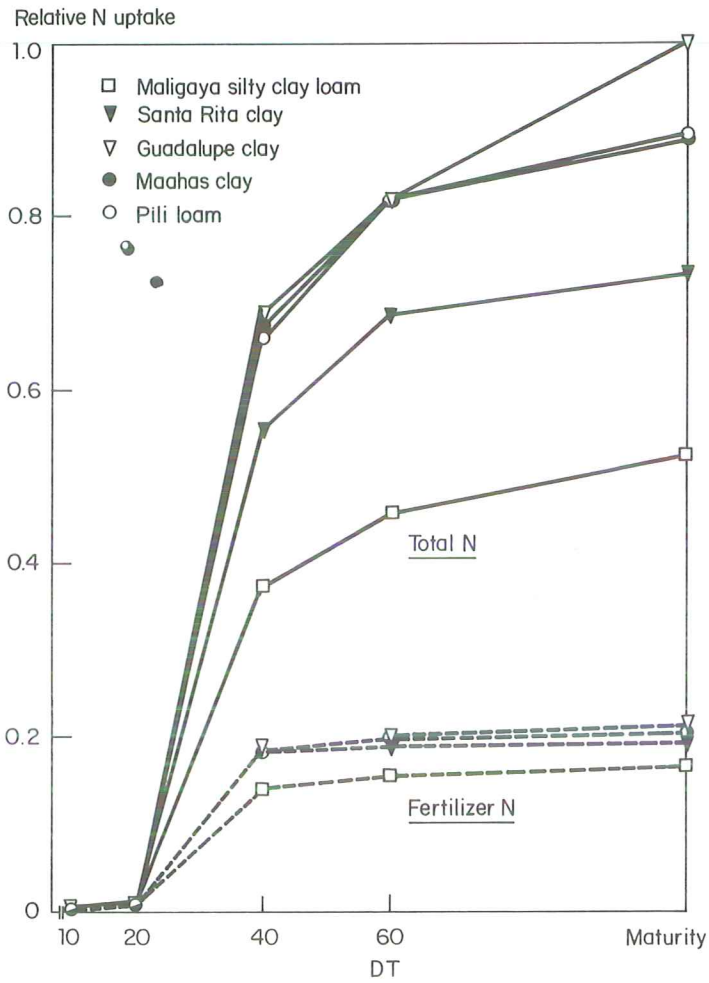
Table 1. Nonexchangeable NH_4^+ contents of the incubated soils at beginning and end of a 1981 dry-season experiment on 3 Philippine soils (13).

Soil	N application rate (kg/ha)	NH_4^+-N in oven-dry soil (mmol/kg)		
		Beginning	End[a]	Δ
Maligaya silty clay loam	0		6.9+++	−3.4
	60	10.3	7.0+++	−3.3
	120		7.5+++	−2.8
Guadalupe clay	0		4.5+++	−0.8
	80	5.3	4.6++	−0.7
	120		4.5+++	−0.8
Santa Rita clay	0		19.0[ns]	+1.5
	60	17.5	16.0++	−1.5
	120		15.7++	−1.8

[a] +++ = significant at 0.1% level, ++ = significant at 1.0% level, + = significant at 5.0% level.



3. Recovery of ^{15}N-fertilizer from 3 soil N fractions and in total N at various sampling times of Maligaya silty clay loam. Laboratory experiment. (H. F. Schnier, K. Mengel, and S. K. De Datta, IRRI-Justus Liebig University Cooperative Project, unpubl.)



4. Relative total and fertilizer N uptake by IR36 rice on 5 Philippine soils. IRRI, October 1982-January 1983. (H. F. Schnier, K. Mengel, and S. K. De Datta, IRRI-Justus Liebig University Cooperative Project, unpubl.). DT = days after transplanting.

Minimizing nitrogen loss with proper management of nitrogen and water

Floodwater chemistry. The pH of the water in flooded rice systems is dominated by aqueous H_2CO_3 in the water and influenced to a large extent by the balance between the opposing biological processes of respiration and photosynthesis. The agronomic significance of the high pH that develops in rice floodwater has been largely neglected as a factor in the direct volatilization loss of NH_3. Earlier results (14) clearly established that the algal population is the major factor affecting the CO_2 equilibrium, the pH of the floodwater, and NH_3 volatilization loss.

Later studies (2) showed that in the dry season after 3 d of fertilizer application there were distinct differences in algal growth in the floodwater because of N application method. Algal growth was vigorous in the floodwater when urea was broadcast and incorporated, but insignificant in the control (no fertilizer N). Vlek and Craswell (25) suggested that the extent of NH_3 loss is strongly dependent on the NH_4^+-N concentration in the floodwater. In our experiments (2), split application of prilled urea (PU) produced the highest concentration of urea plus NH_4^+-N in the floodwater (58 mg/kg in the dry season). Deep placement, on the other hand, resulted in negligible concentration of fertilizer N in the floodwater.

In a study during the 1983 wet season, PU was broadcast into various depths of floodwater (0, 2.5, 5, and 10 cm) and incorporated with a hand shovel; more than 50% of that applied (39 kg N/ha as basal dose) was recovered in the floodwater irrespective of the water depth. However, the least amount of total N (urea + NH_4^+-N) was recovered in the floodwater when urea was broadcast onto mud and then incorporated into the soil (Fig. 5).

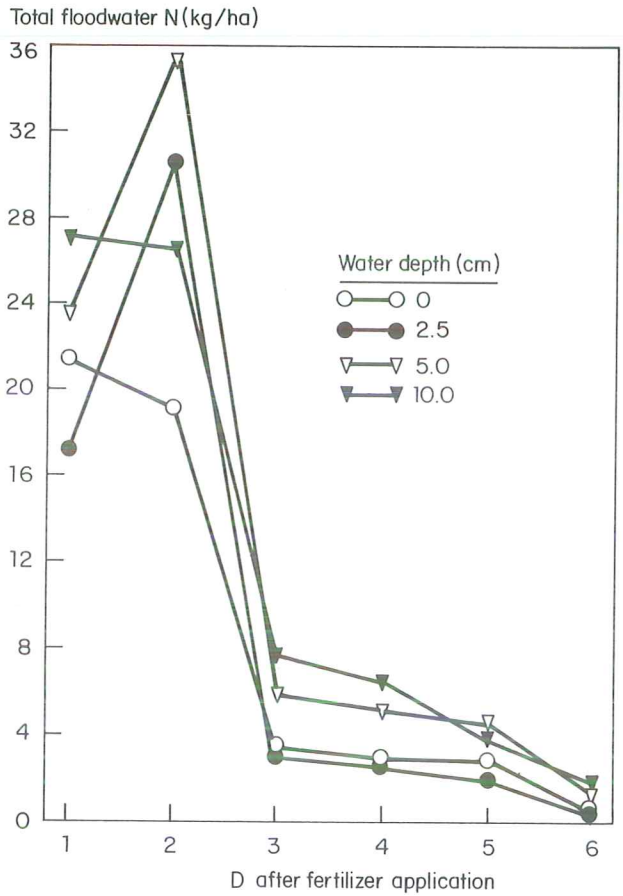
In another 1983 wet season trial, the farmers' timing (broadcasting the first N dose into the floodwater at 10 DT) produced the most floodwater N (Fig. 6). The results demonstrated that broadcast and incorporation of N fertilizers in a field with standing water before transplanting leads to high N loss and minimizes N use efficiency. These findings are significant, as the price of fertilizer N is high and fertilizer subsidies are low or have been withdrawn in many rice-growing countries in Asia.

Nitrogen loss in a calcareous soil. Potential N loss was studied in a calcareous San Manuel silty clay soil (pH 7.2, CEC 39 meq/100 g soil, exchangeable Ca 30 meq/100 g soil, organic matter 2.4%, total N 0.15%) in Pangasinan, Philippines.

With the researchers' split (2/3 basal incorporated and 1/3 at 5-7 d before panicle initiation [DBPI], the floodwater pH increased to 9.1 at 5 d after N application and dropped to 7.5 the following day (Fig. 7). With the researchers' split, the total (urea + NH_4^+-N) N in the floodwater the first day after fertilizer application was 140 ppm but dropped to a negligible level the following day. Nitrogen was not recorded in the floodwater with deep point placement of N fertilizer similar to the nonfertilized control.

These results suggest that even in a calcareous soil, deep point placement of N fertilizer results in minimum N loss.

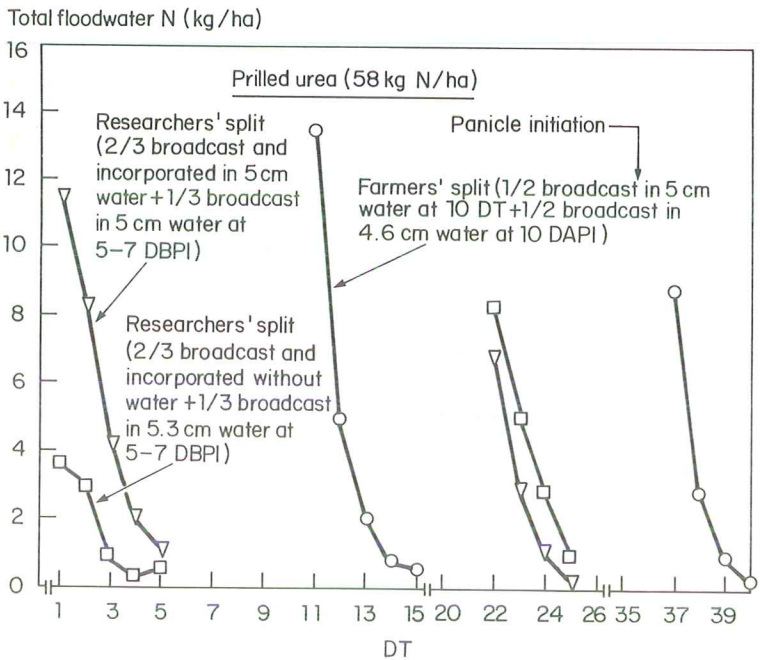
Ammonia volatilization. Ammonia, a readily identifiable product of N mineralization, is formed continuously in the soil and water of a flooded soil system.



5. Total floodwater N (urea-N + NH_4^+-N) after prilled urea was incorporated at 39 kg N/ha (2/3 of the targeted rate incorporated lightly with a hand shovel and the remaining 1/3 was topdressed at 5-7 d before panicle initiation). IRRI, 1983 wet season.

Ammonia volatilization loss from floodwater may occur on a soil moderately to slightly acidic, although losses are usually highest on alkaline soils. Many physicochemical and biological factors in a flooded soil-water-atmosphere system simultaneously influence NH_3 volatilization (4, 20). Ammonia volatilization losses in flooded soils range from negligible to almost 60% of applied N (20). In recent studies using closed systems with air exchange and an acid trap (11, 15), the NH_3 loss from $(NH_4)_2SO_4$ was 0.2-6.8% and that from urea 1-20%. In a study using micrometeorological techniques it was 5-11%.

Most recently, using direct measurements of NH_3 loss in the field at IRRI and at the Maligaya Rice Research and Training Center with micrometeorological techniques, Fillery et al (10) found that NH_3 loss with surface topdressing at 14 or 27 DT varied from 27

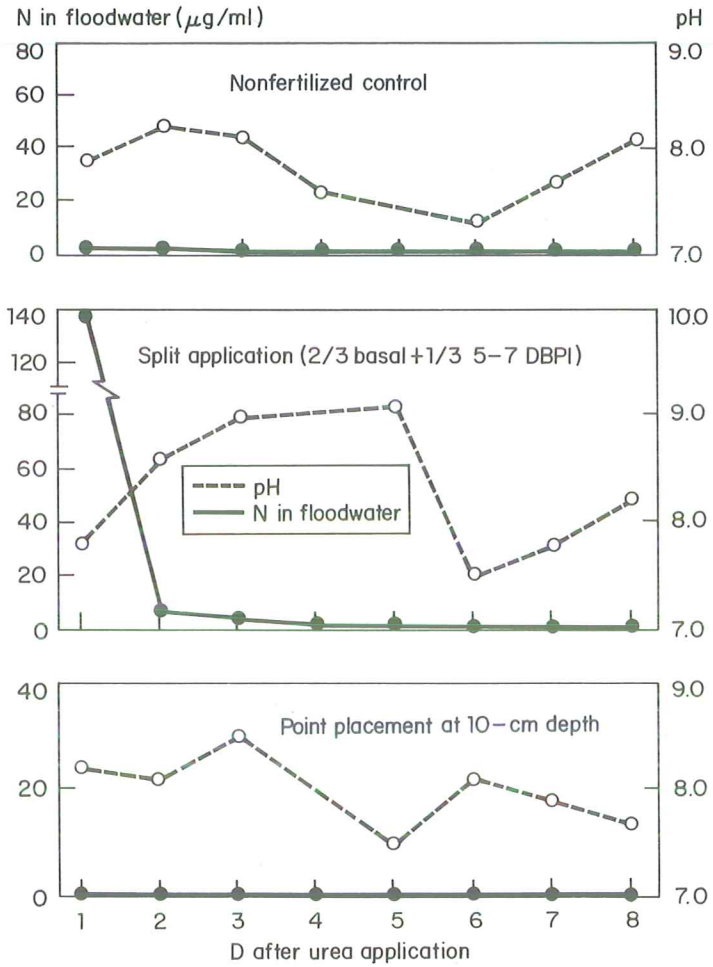


6. Urea fertilizer surface broadcast or incorporated with standing water produced high amounts of N (urea-N + NH_4^+-N) in the floodwater at 1300-1400 h, indicating higher N losses and low efficiency. IRRI, 1983 wet season. DBPI = days before panicle initiation, DT = days after transplanting, DAPI = days after panicle initiation.

to 47%. Rates of NH_3 loss were limited to 10-15% when urea was applied at the panicle initiation stage.

The results of Mikkelsen et al (14) and Fillery et al (10) suggest that the NH_4^+ forms of fertilizer such as urea and $(NH_4)_2SO_4$, broadcast into water, are highly susceptible to NH_3 volatilization. The magnitude of loss varies with the NH_4^+ concentration in the floodwater, the biochemical activities of the aquatic biota and their effects on the pH of the floodwater, N source, and time and method of application. Thorough incorporation of NH_4^+-N fertilizers into the soil also minimizes NH_3 volatilization loss (7, 14).

Urease inhibition and minimizing potential ammonia volatilization losses. The potential of urease inhibitors for reducing NH_3 volatilization loss from broadcast urea in lowland rice has been evaluated under greenhouse conditions at the International Fertilizer Development Center. In IRRI field studies on Maahas clay (Andaqueptic Haplaquolls), the urease inhibitor PPD (phenylphosphoro-diamidate) appeared to have delayed the hydrolysis of urea broadcast into the floodwater at 20 DT (7). In Maligaya clay (Entic Pellusterts, pH 5.7, CEC 27 meq/100 g soil, organic matter 1.9%, total N 0.1%), when urea was applied with 1% PPD,



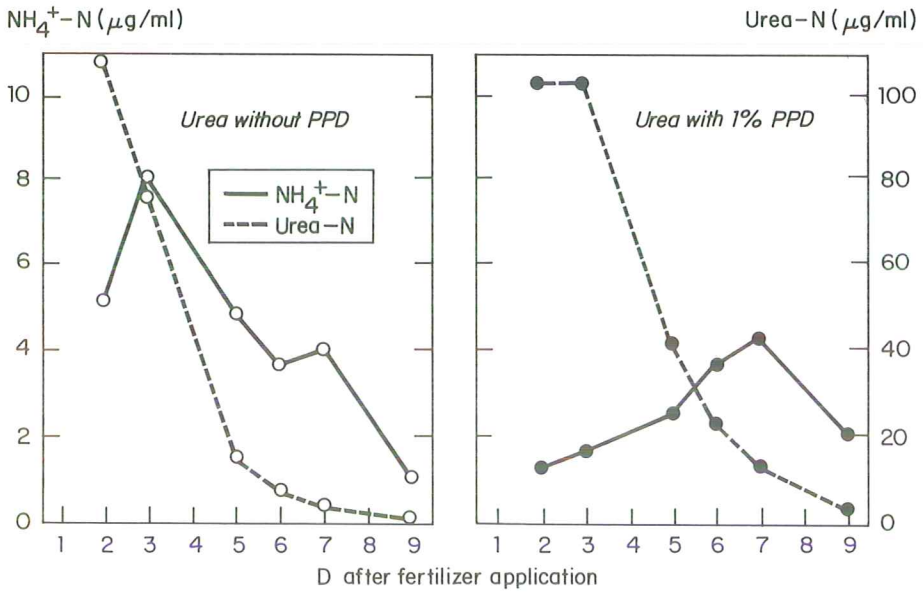
7. Changes in pH and total N concentration of floodwater as affected by different methods of urea application on a calcareous San Manuel clay loam, Laoac, Pangasinan, 1983 dry season. DBPI = days before panicle initiation.

the hydrolysis of urea was delayed and the buildup of NH_4^+-N was reduced (Fig. 8). The addition of the urease inhibitor PPD along with urea reduced the NH_3 loss from 22 kg N/ha to 12 kg N/ha (9).

The magnitude of NH_3 loss from the floodwater-soil system is large enough to demand further attention in the coming years.

ALTERNATIVE PRACTICES FOR INCREASING NITROGEN-USE EFFICIENCY IN LOWLAND RICE

Low soil fertility, particularly N deficiency, is an important constraint in the rice-growing countries in South and Southeast Asia. The steadily increasing cost



8. Effect of phenylphosphorodiamidate (PPD, 1%) on the concentration of urea and ammonium in floodwater in Maligaya clay. Maligaya Rice Research and Training Center, Nueva Ecija, Philippines, 1983 dry season.

of fertilizers has resulted in more emphasis on improved management of N fertilizers for efficient use in lowland (irrigated and rainfed) rice. One way to increase fertilizer efficiency, using the same amount of N absorbed by the plant, is to apply the fertilizer at the time it best meets the demand of the rice crop.

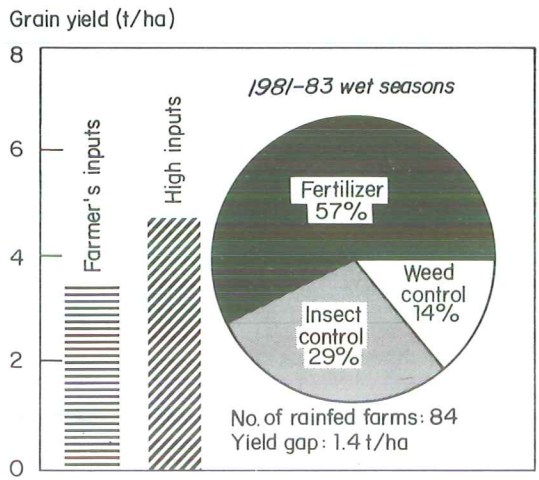
A large number of field trials in farmers' fields in the Philippines suggest that many farmers obtain low yields because they apply low rates of fertilizer N, and inefficiently at that. Even under rainfed conditions during the 1981-83 wet seasons, 57% of a 1.4 t/ha yield gap in 2 Philippine provinces was explained by the low rates of fertilizer N and poor timing of application used by 84 farmers (Fig. 9).

In recent years the following alternative concepts have been evaluated at IRRI and elsewhere to increase N-use efficiency in lowland rice:

- varietal differences in N-use efficiency,
- improved timing of N application,
- deep placement of N fertilizer,
- controlled-release N fertilizers, and
- use of nitrification and urease inhibitors.

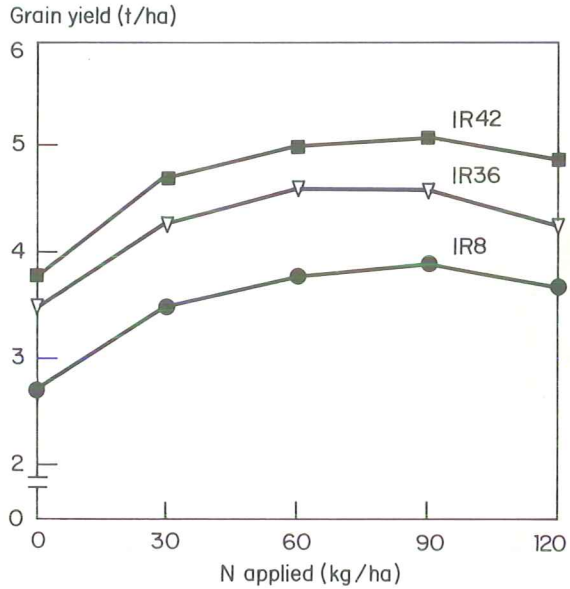
Varietal differences in nitrogen-use efficiency

In developing practices that will increase fertilizer-use efficiency in lowland rice, it is critical to exploit varietal differences in the ability to use soil and fertilizer N.



9. Average yields with farmers' and high inputs and contributions of fertilizer, insect control, and weed control to the yield gap in rainfed farms in Tarlac, and in Libmanan and San Fernando, Camarines Sur, Philippines, 1981-83 wet seasons.

Results from 1976-1982 experiments at four experiment stations in the Philippines clearly suggest that IR42 uses soil and fertilizer N more efficiently than IR36, the world's most widely grown variety (Fig. 10). IR8, which is susceptible to insects and diseases, performed poorly at all N levels.



10. Grain yield response of 3 rices to different N levels. Data are averages for IRRI and 3 experiment stations of the Philippine Bureau of Plant Industry (Maligaya, Bicol, and Visayas), 1976-82 wet seasons.

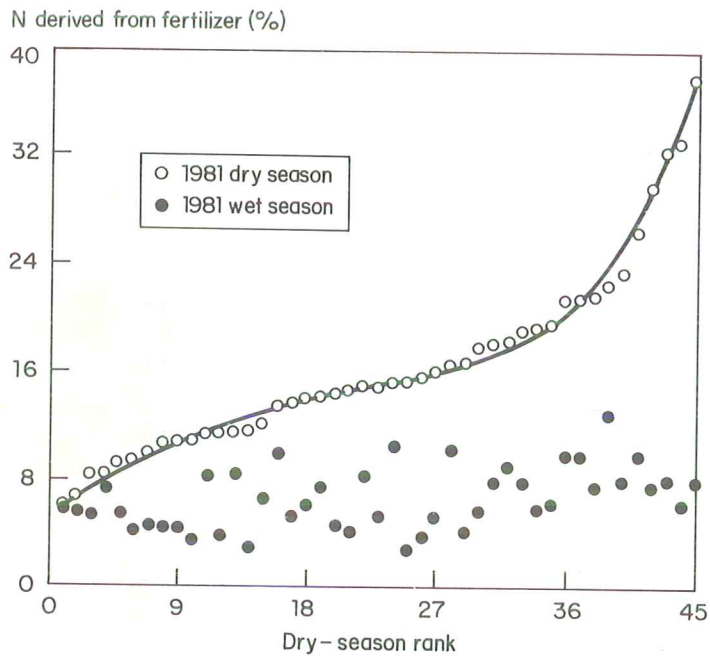
Our recent results with ^{15}N-depleted $(NH_4)_2SO_4$ (IRRI-University of California, Davis Cooperative Project, unpubl.) suggest that some varieties depend primarily on soil N and others use fertilizer N more efficiently. Varietal differences in the use of N are clearer in the dry season than in the wet (Fig. 11).

In delineating significant differences among varieties in their ability to use soil and fertilizer N, the following criteria must be met:

- The plant behavior with respect to fertilizer-use efficiency must be consistent in repeated experiments, and
- The plant characteristics associated with N-use efficiency must be identified (S. K. De Datta, IRRI, and F. E. Broadbent, U. C. Davis, unpubl.).

Timing of nitrogen application

Applying the first dose of N to a puddled field without any standing water and thoroughly incorporating it into the soil and then introducing water at 4 DT greatly increased the efficiency of fertilizer N. The final topdressing of N should be made at 5-7 DBPI into floodwater not exceeding 5 cm. In farmers' fields in three Philippine provinces, use of these techniques increased



11. Comparison of % N derived from fertilizer in 1981 dry and wet seasons with varieties and lines sorted according to dry season rank (S. K. De Datta and F. E. Broadbent, IRRI-U. C. Davis Cooperative Project, unpubl.).

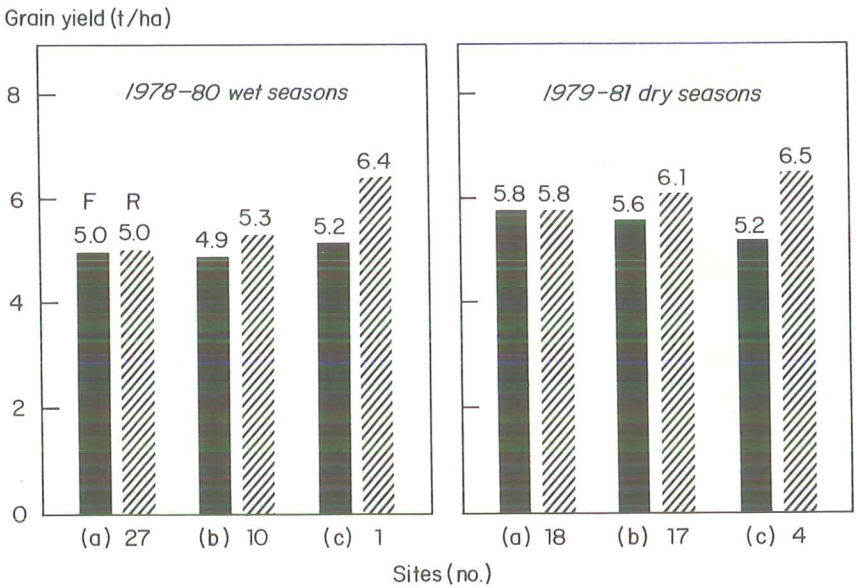
grain yield over farmers' timing by 0.7 t/ha in 21 of 39 trials in the dry season, and by 0.5 t/ha in 11 of 38 trials in the wet season (Fig. 12).

When the data for 167 farmers' field trials (134 irrigated and 33 rainfed) in 1978-1983 were averaged, the grain yield increase due to the researchers' split (2/3 basal incorporated and 1/3 topdressed 5-7 DBPI) over the farmers' method and timing of N application was 0.4 t/ha. This technology is highly relevant in farmers' fields, as there appeared to be no risks to the farmers (Fig. 13).

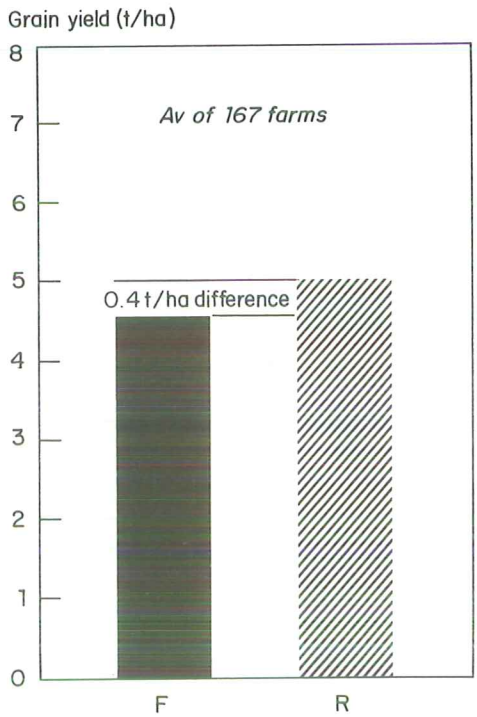
Deep placement

Conceptually, deep point placement has been known since the classical work of Shioiri (22) in Japan and the subsequent research by Vacchhani (24) in India. Detailed literature reviews on the subject are found elsewhere (4, 15).

Results (2) of using ^{15}N-labeled urea in the field microplots suggest that point placement gave the highest yield of 6.4 t/ha with an efficiency of 51 kg rough rice/kg N in the dry season. In the dry season, fertilizer ^{15}N recovery by the rice plant at harvest (grain straw) was as high as 75% with point placement of urea supergranules (USG). Nitrogen-15 balance data show that with point placement of USG, only 4-5% of the applied N was unaccounted for after harvest of both the dry and wet season crops (3).



12. Average yields with farmers' (F) and researchers' (R) timing of N application, 3 study areas (Nueva Ecija, Laguna, and Camarines Sur) in the Philippines, 1978-81. a = no significant yield difference between F and R, b = R yielded significantly higher than F at some N rates, c = R yielded significantly higher than F at all N rates.

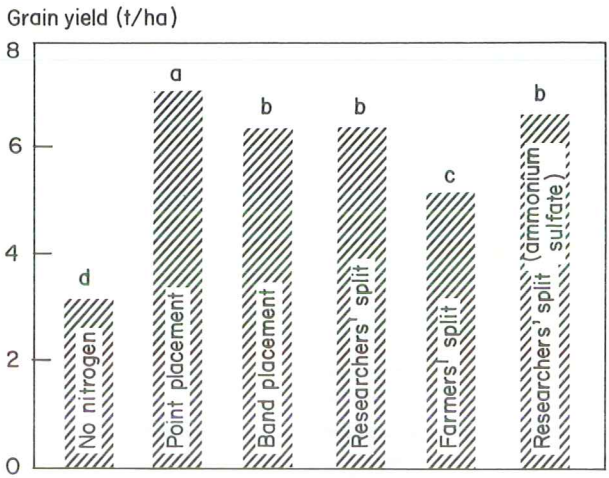


13. Average yields with farmers' (F) and researcher's (R) timing of N application in 134 irrigated and 33 rainfed farms in 4 provinces (Nueva Ecija, Laguna, Camarines Sur, and Tarlac), Philippines, 1978-83.

In recent field studies in a calcareous soil in the Philippines (San Manuel clay loam), the grain yield response to deep point placement at 10-cm depth resulted in the highest grain yield, 7.1 t/ha (Fig. 14). These results suggest that even in calcareous soils, deep placement of N fertilizer results in high grain yield. Urea and $(NH_4)_2SO_4$ gave similar yields (Fig. 14). Balance data for N-15 are being computed for this site.

Several machines designed to make deep placement of N fertilizer relevant at the farm level by reducing application time have been developed and tested in Japan, China, the Netherlands, and at IRRI. During the 1983 wet season, four most promising IRRI-designed placement machines were evaluated and compared with hand deep point placement of USG.

Band placement of urea with either the oscillating plunger or spring auger machine produced (Table 2) the two highest grain yields (5.1 t/ha and 4.7 t/ha), comparable to the yield obtained with hand point placement of USG (4.6 t/ha). Hand point placement of USG was the most labor intensive (47 h/ha).



14. Grain yield of IR58 as affected by different methods of urea fertilizer application at 87 kg N/ha on a calcareous San Manuel clay loam. Laoac, Pangasinan, Philippines, 1983 dry season. Bars headed by the same letter are not significantly different from each other at the 5% level.

In selecting machines for deep placement of N fertilizers, the following criteria were used:

- ease of operation in puddled field,
- time taken to apply the desired rate of fertilizer,
- similarity to the target application rate,
- effectivity of the machine in applying fertilizer to the reduced soil layer (by monitoring NH_4^+- and urea-N in the floodwater after fertilizer application), and
- grain yield and N-use efficiency (kg rice/kg N).

These machines are being evaluated extensively in farmers' fields in the Philippines and in a number of countries under the International Network on Soil Fertility and Fertilizer Evaluation for Rice (INSFFER) program.

Slow and controlled-release fertilizers

Fertilizer shortages, plus heavy losses of fertilizer N in rice fields (2, 3, 10, 14, 20, 25) when application rates are high, as in the case of modern varieties, have led fertilizer technologists to develop fertilizer materials for more efficient use.

Fertilizers that release their plant nutrients slowly throughout the growing season, or longer, have a number of proven or potential advantages. Earlier studies suggested that slow-release fertilizers such as S-coated urea (SCU) greatly reduce NH_3 volatilization loss (14) and sustain the crop with adequate N nutrition throughout the growing season (7). INSFFER results confirm these findings (6).

Table 2. Effect of various fertilizer application techniques using hand or machine on the actual amount of N applied and grain yield of IR58 rice. IRRI, 1983 wet season.

Urea source	N application		Water depth during basal fertilizer application (cm)	Grain yield[a] (t/ha)
	Method	Rate (kg/ha)		
–	No fertilizer nitrogen	0	–	2.9 c
Prilled	Band placement by spring auger	56	4.6	4.7 ab
Prilled	Band placement by oscillating plunger	58	4.8	5.1 a
Supergranule	Point placement by deep plunger	58	4.9	4.4 ab
Supergranule	Point placement by press wedge	46	5.1	4.3 b
Supergranule	Point placement by hand	58	5.3	4.6 ab
Prilled	Researchers' split	58	5.0	4.2 b
Prilled	Researchers' split	58	0	4.8 ab
Prilled	Farmers' split[b]	58	5.0	4.3 b

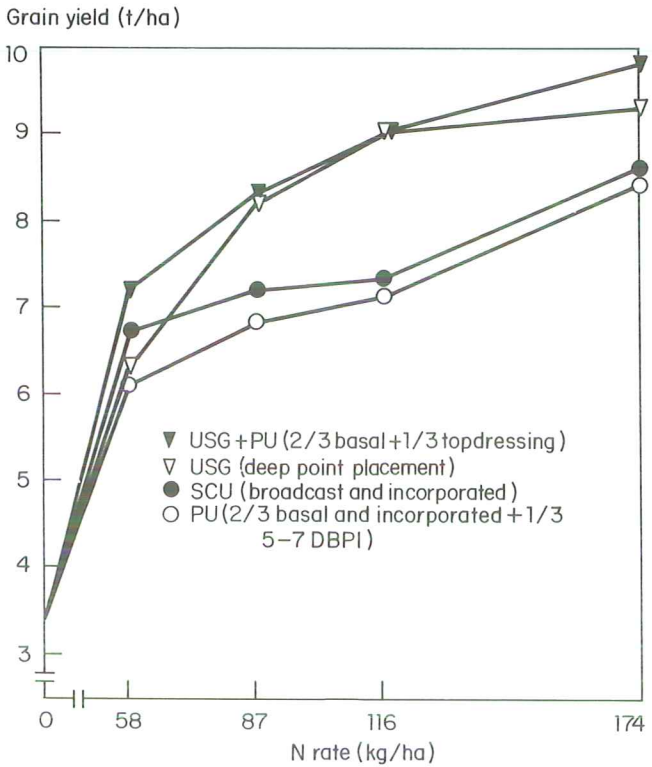
[a]Separation of means by Duncans multiple range test at the 5% level. [b]10 d after transplanting and 10 d after panicle initiation.

In a farmers' field experiment comparing SCU with deep point placement of USG and split application of PU, the highest grain yield of 9.8 t/ha was obtained at 174 kg N/ha with a combination of USG deep point placement as a basal dose of 116 kg N/ha and topdressing of PU at 58 kg N/ha at 5-7 DBPI. However, there was no significant difference between all basal SCU incorporated and all basal deep point placement of USG (Fig. 15).

Use of nitrification and urease inhibitors

Nitrification inhibitors. Another approach used to achieve controlled availability of plant nutrients is the use of nitrification inhibitors. In almost all cases, the inhibitor is intended to block the conversion of NH_4^+-N to NO_3^--N by inhibiting Nitrosomonas growth or activity. Early results with nitrification inhibitors were reported elsewhere (18, 19).

Nitrification inhibitors appeared promising in Japan and in Arkansas, USA (25), but not in Louisiana, USA (23). In India, in tests with indigenous materials with nitrification-inhibiting properties, a 22% increase in rice yield was attributed to treatment of urea with an acetone extract of neem (Azadirachta indica A. Juss; 18). Recently, the effectiveness of dicyandiamide (DCD) as a nitrification inhibitor in



15. IR36 produced 9.8 t/ha in a farmer's field trial in Calauan, Laguna, Philippines with a daily productivity of 111 kg/ha. 1983 dry season. USG = urea supergranules, PU = prilled urea, SCU = sulfur-coated urea, DBPI = days before panicle initiation.

various types of rice culture (lowland, upland, and deep water) and stand establishment methods was evaluated. In the 1982 dry season, IRRI results showed that PU with 10% or 15% DCD and forestry-grade SCU, broadcast and incorporated during the final harrowing, and split-applied PU with DCD in lowland IR36 rice produced comparable grain yields (Table 3). The treatments $(NH_4)_2SO_4$ + DCD and $(NH_4)_2SO_4$ without DCD gave similar results (Table 3).

Urease inhibitors. In a greenhouse study by Vlek et al (24), PPD retarded urea hydrolysis and delayed the appearance of aqueous NH_3 in the floodwater -- findings confirmed by field results at IRRI (7) and Maligaya (9; Fig. 8). Although PPD retarded urea hydrolysis, it did not increase grain yield (Table 4) and total N uptake.

However, in recent tests, the application of PPD with urea significantly increased plant N uptake and grain yield on Maahas clay when urea or urea + 1% PPD was topdressed at 26 DT. On the other hand, grain yield was not increased in a similar experiment on Maligaya clay where urea or urea + 1% PPD was applied at 18 DT

Table 3. Effect of N sources and application method on the grain yield of IR36 rice. IRRI, 1982 dry season.

N source[a]	Application		Grain yield[b] (t/ha)
	Rate (kg N/ha)	Method	
No fertilizer N	0	–	4.2 d
Prilled urea	90	Basal, surface broadcast	5.6 c
Prilled urea	90	Researchers' split	6.4 ab
Prilled urea + 10% DCD	90	Basal, broadcast & incorporated	6.7 a
Prilled urea + 15% DCD	90	Basal, surface broadcast	5.7 bc
Prilled urea + 15% DCD	90	Basal, broadcast & incorporated	6.9 a
$(NH_4)_2SO_4$	90	Researchers' split	6.3 abc
$(NH_4)_2SO_4$ + 10% DCD	90	Basal, broadcast & incorporated	6.4 ab
$(NH_4)_2SO_4$ + 15% DCD	90	Basal, broadcast & incorporated	6.9 a
Forestry grade SCU	90	Basal, broadcast & incorporated	6.7 a
Prilled urea	150	Researchers' split	6.9 a
$(NH_4)_2SO_4$	150	Researchers' split	6.6 a

[a]DCD = dicyandiamide, SCU = sulfur-coated urea. [b]Av of 4 replications. Separation of means by Duncan's multiple range test at the 5% level.

Table 4. Effect of source and application method of urea, with and without PPD, on the grain yield of IR36 rice. IRRI, 1982 dry and wet seasons.

Treatment[a]	Grain yield[b] (t/ha)	
	Dry season	Wet season
No fertilizer N	2.7 d	3.1 c
2/3 basal, incorporated + 1/3 at PI		
Prilled urea	5.1 ab	4.0 ab
Urea + 5% PPD	5.2 ab	4.2 ab
Urea + 2% PPD	5.0 ab	4.6 a

[a]PI = panicle initiation, PPD = phenylphosphorodiamidate. N levels were 100 kg/ha in the dry season and 60 kg/ha in the wet. [b]Av of 4 replications. Separation of means in a column by Duncan's multiple range test at the 5% level.

(12). Additional research is needed to delineate carefully the benefits of urease inhibitors in minimizing N loss and increasing N-use efficiency in lowland rice.

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AVAILABILITY AND MANAGEMENT OF PHOSPHORUS IN WETLAND SOILS IN RELATION TO SOIL CHARACTERISTICS

R. B. DIAMOND

The yield responses of wetland rice to P fertilization are not as common as those of upland crops. Oxisols, Ultisols, Vertisols, and certain Inceptisols, particularly Andepts and acid sulfate soils, are the principal ones that are P deficient for wetland rice. The greater availability of P under submerged conditions than under aerobic conditions is largely attributed to differences in the oxidation-reduction state and the resultant influence on the status of Fe in soil. However, differences in pH, microbial activity, and soil water content and changes in adsorption characteristics due to wetting and drying, as well as the special attributes of the rice plant, may explain differences in the response of rice and upland crops to P. The Olsen method for estimating P availability using the air-dry soil is the most universally applicable method for all types of soils. Surface application of fertilizer P from transplanting to 4 WT generally gives as good a response as mixing fertilizer P with the soil before transplanting. Dipping seedling roots into a P-soil slurry before transplanting has reduced fertilizer P requirements in China and India. Finely ground, moderately to highly reactive phosphate rock has a widespread potential for use on acid soils.

Although P deficiency is not as common in flooded rice as in upland crops, response to P occurs in millions of hectares of wetland rice (10). Deficiencies occur principally on Ultisols, Oxisols, Vertisols, and certain Inceptisols, particularly Andepts and acid sulfate soils.

Phosphorus availability in soils is exceedingly complex and is made more so by the alternate wetting

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and drying that occurs in wetland rice culture. There is more literature on P transformations and availability in soil than on any other single soil science subject. Yet, there is no clear understanding as to whether strictly solubility or sorption relationships control the availability of P to plants.

This paper summarizes some of the important factors influencing P availability in wetland soils and reports findings relating to field management of fertilizer P for greater use efficiency by the rice crop.

PHOSPHORUS AVAILABILITY

Generally, soil P is illustrated by the following relation:

$$\text{Solution P} \rightleftharpoons \text{labile P} \rightleftharpoons \text{nonlabile P}$$

The immediate source of P for plants is the soil solution. Labile P is defined as P that is readily exchanged with soil P (31). Equilibrium between labile P and solution P is rapidly established. True equilibrium is seldom, if ever, established between labile and nonlabile P. Actually, these categories are arbitrary since exact boundaries cannot be precisely delineated.

Sample et al (38) conclude that many researchers view P retention in soil as a continuum embodying precipitation, chemisorption, and adsorption. This is particularly true if the processes are viewed throughout the entire zone of soil influenced by a fertilizer application and through a time span of a growing season or longer.

In practical terms P transfer from solid to solution phases in a continuing depletion system (plant sink) may be considered as dissolution of precipitated P or as P desorption. The nature of the chemical identities in soil depends on

- types and quantity of clay;
- quantities of Fe, Al, and Ca;
- organic matter;
- P status;
- pH; and
- oxidation-reduction state.

Regardless of the chemical identities of soil P, the following release properties control the supply of P to the plant roots:

- quantity -- reserve P (labile P),
- intensity -- P potential (concentration of soluble P),
- capacity -- relative constancy of solution P concentration (buffer capacity) during P depletion (gradients relating quantity to intensity), and
- diffusion -- P movement to roots through soil solution.

Iron, aluminum, and calcium

When P-fertilizer granules are added to the soil and are dissolved by soil water, very high concentrations of P and accompanying cations exist in the immediate vicinity of the placement site. Minerals are precipitated under conditions of supersaturation of the soil solution. Thus, reactions occur among the phosphate, soil constituents, and nonphosphatic fertilizer compounds; they result in the formation of less soluble phosphates and lower P concentration of the soil solution.

Lindsay (26) has depicted the solubility relations of various Ca, Fe, and Al phosphates, and pH. Liming of acid soils, which contain Fe and Al phosphates, can be expected to increase phosphate solubility. But at pH >6.5, Ca phosphate can precipitate and lower P solubility.

Sanchez and Uehara (40) report that 2 meq exchangeable Al/100 g soil may fix up to 102 ppm when hydrolyzed. Correlations between P retention and exchangeable Al are not always satisfactory because of incomplete hydrolysis. However, it is also known that Al oxides and hydrous Al oxides are related to P sorption.

In addition to solubility relations among P, Fe, Al, and Ca, all of which influence the availability of P, minerals of these cations influence P adsorption.

Type and quantity of clay

Phosphate adsorption by soils involves reactions at the surfaces of particles; therefore, for soils of similar mineralogy the quantity of P undergoing adsorption is closely related to the surface area. Olsen et al (30) reported that P uptake and percentage of apparent fertilizer P recovery decreased with increasing clay content of previously fertilized calcareous soils. Juo and Fox (21) found a close correlation between soil sample surface area and standard P adsorption (adsorption in equilibrium with 0.2 µg P/ml in solution) for 28 soils from savanna and rain forest zones of west Africa.

In a review of Indian data, Goswami and Banerjee (17) reported that availability percentage of added P was about equal to 100 minus the clay percentage for Vertisols and about 100 minus two times the clay percentage for Ultisols and Entisols. This illustrates that fertilizer P availability is influenced by factors other than clay content.

Mineralogy is the key factor affecting P-sorption characteristics of soils. Juo and Fox (21) classified soils into five categories based upon P-sorption characteristics of the dominant mineral (Table 1). They ranked P adsorption by soils according to mineralogy as

Table 1. Classification of soils according to P sorption and standard P requirements (20).

Standard P requirement (μg P/g soil)	Scale	Usual mineralogy encountered
10	Very low	Quartz, organic materials
10-100	Low	2:1 clays, quartz, and 1:1 clays
100-500	Medium	1:1 clays with oxides
500-1000	High	Oxides, moderately weathered ash
1000	Very high	Desilicated amorphous material

follows: quartz = Al-free organic matter < 2:1 clays < 1:1 clays < crystalline oxides of Fe and Al < amorphous oxides of Al and Fe.

More recently Bajwa (2) concluded from studies of clay fractions from Philippine rice soils that P adsorption was in the order montmorillonite < vermiculite < halloysite < x-ray amorphous < kaolinite.

Fox and Searle (15) reported that amorphous materials low in Si are reactive to P. Phosphate retention by a sequence of volcanic deposits was inversely related to Si concentration.

Organic matter

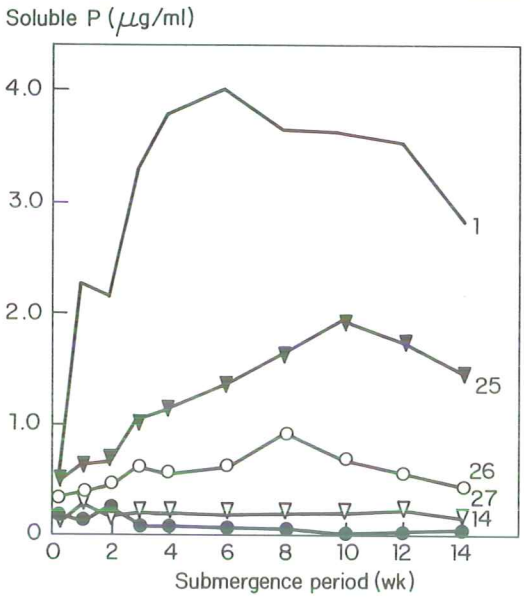
Organic anions are adsorbed by Fe and Al oxides and hydrous oxides and thus compete for P-adsorption sites (15). Sanchez and Uehara (40) state that this is one reason why topsoils of Oxisols and Andepts whose texture and mineralogy are similar to their subsoils fix less P than the subsoils. Also, organic anions may reduce P adsorption because they are strong chelates for complexing Fe and Al.

Soil submergence

Soon after soil submergence, O_2 concentrations are lower. Ponnamperuma (37) reported that the pH of acid soils increases largely because of the reduction of Fe but that the stable pH of submerged soils is regulated by PCO_2. The pH values of submerged calcareous and sodic soils are lower than those of aerobic soils because of the accumulation of CO_2. Ferric and Al compounds of P release P as pH increases, whereas Ca compounds of P liberate P as pH decreases. Generally, after soil submergence, concentrations of water-soluble P increase (Fig. 1). Ponnamperuma (36) and Patrick and Mahapatra (33) reported marked increases in the availability of native and added phosphates in flooded soils over those in well-drained soils. Yield responses to P are not as frequent in flooded rice as in upland crops (11).

Patrick and Khalid (32) observed that anaerobic soils released more P to solutions low in soluble P and adsorbed more P from solutions high in soluble P than

Soil no.	Texture	pH	OM (%)	Fe (%)
1	Sandy loam	7.6	2.3	0.18
4	Clay	4.6	2.8	2.13
25	Sandy loam	4.8	4.4	0.18
26	Clay loam	7.6	1.5	0.30
27	Clay	6.6	2.0	1.60



1. Kinetics of water-soluble P in some submerged soils (36).

did aerobic soils. Khalid et al (24) obtained similar results with two Alfisols and three Inceptisols from Louisiana and found that of the soil properties tested, oxalate-extractable Fe is the most important contributor to P adsorption by flooded soils. They suggested that Fe^{3+} oxyhydroxide more firmly adsorbs P but has less surface area exposed to solution P than gel-like hydrated Fe^{2+} oxides or $Fe(OH)_2$.

Willett and Higgins (45) found results consistent with domination of P adsorption by Fe^{2+} hydrous oxides during the flooded phase and by poorly crystalline Fe^{3+} hydrous oxides during the postflooding phase.

De Datta et al (12) showed that within 4 days of equilibration, added P remaining in solution was lowest in acid Latosols (kaolin), moderately high in montmorillonite soils, and essentially unchanged in calcareous soil.

Turner and Gilliam (41, 42) attributed to enhanced P diffusion the greater amount of anion resin-adsorbable P in water-saturated alkaline soils relative

to moist soils. Thus, the increased rate of P diffusion in water-saturated soils may be partly responsible for the greater P availability to plants in submerged soils than to upland crops.

Alva et al (1) postulated that the increased microbial activity in the presence of physiologically active roots was responsible for P mobilization, while the capacity of rice plants to reoxidize the rhizosphere, by secretion of O_2 from roots, during the later growing period was responsible for P immobilization. They suggested that lowland rice plants have a mechanism for regulating the contrasting changes in P availability in the rhizosphere depending on P requirement by the plants or P availability in soil, which in turn is responsible for the generally poor response to P fertilization.

Sanchez (39) listed six causes of general increased P availability upon soil submergence:

- reduction of Fe-P,
- dissolution of occluded P,
- hydrolysis of Fe and Al-P in acid soils,
- increased mineralization of organic P in acid soils,
- increased solubility of Ca-P in calcareous soils, and
- greater diffusion of P.

ESTIMATING FERTILIZER REQUIREMENTS

A large number of soil test procedures are used to estimate available P in soils. Ideally, the procedure should estimate plant-available forms from various soils, be accurate and rapid, and provide values correlated with each crop response under various conditions.

An assessment of P status by chemical tests should consider relationships among quantity, intensity, capacity, and diffusion, and factors influencing these components of P supply (22). The quantity and intensity factors are a function of amounts and crystallinity of hydrated oxides of Fe and Al in acid and neutral soils, and of exchangeable Ca and $CaCO_3$ in calcareous soils. Chang and Juo (6) showed that alkaline solutions and those containing NH_4F preferentially extract Al-P, and acid solutions preferentially extract Ca-P. In addition to being limited in use over all soils, soil tests characterize either the quantity factor (with strong extractants) or the intensity factor (with weak extractants). For wetland rice there are additional problems: 1) tests on air-dry soil may not reflect P status after submergence, and 2) P availability generally increases after submergence, but the degree of change depends upon soil characteristics.

Dabin (9) stated that for rice grown in pots with soils where Fe-P dominates, alkaline extractants give the best correlation with response to fertilizer P. Mahapatra and Patrick (28) and Cholitkul and Tyner (8) similarly concluded that, for air-dry samples of wetland rice soils, the extractants must be rather Fe-P specific.

Chang (3) summarized soil test work on rice soils in India during the early 1960s and concluded that none of the eight methods tested gave good correlation with rice response in the field. In pot studies the Olsen method gave high correlation and was far better than the other methods. Goswami and Banerjee (17) reported that more recent soil test work on rice soils in India indicates that the Olsen method is suitable for predicting field responses to fertilizer P. Verma and Tripathi (43), by stepwise regression analysis, found that Fe-P was the most important variable contributing to total variation in extractable P by the Olsen, Bray No. 1, and Bray No. 2 methods in air-dry and waterlogged Alfisols. They reported that P extracted by the Bray No. 2 method correlated well with rice growth under waterlogged conditions in the greenhouse, and suggested that this method can be used on air-dry soil samples to predict rice response to P fertilization (44).

Chang (5), after reviewing results from several countries, concluded that Olsen and Bray No. 1, but especially Olsen, are more universally applicable to all types of soils. His results from 31 soils showed that aerobic and anaerobic P determined by the Olsen method were highly correlated, regardless of pH, and differed little in value. Bray No. 1 and Bray No. 2 were less satisfactory, and the Truog method was unsatisfactory.

In recent years, there have been attempts to use P adsorption isotherms to predict fertilizer P requirements. The amount of P adsorbed at a standard supernatant concentration has been used as an estimate of fertilizer P required. A problem foreseen for this method is that it does not account for differences in buffer capacity and diffusion rate in various soils. Also, different supernatant P concentrations would likely need to be considered, depending upon the crop to be grown. Kemprath and Watson (22) concluded that the method is not suited for routine testing, but can serve to characterize soils and group them for making fertilizer recommendations.

Recently, researchers at the International Rice Research Institute have attempted to develop P adsorption isotherms under reduced soil conditions and relate the data to fertilizer P needs. It appears that the external P requirement (P concentration in solution for optimal growth) for rice may be about 0.07 µg/ml.

It is too early to speculate on the possible use of this approach for estimating fertilizer P requirements for rice.

PHOSPHORUS MANAGEMENT

Correct management of fertilizer P involves decisions about the choice of phosphate source, timing, and method of application.

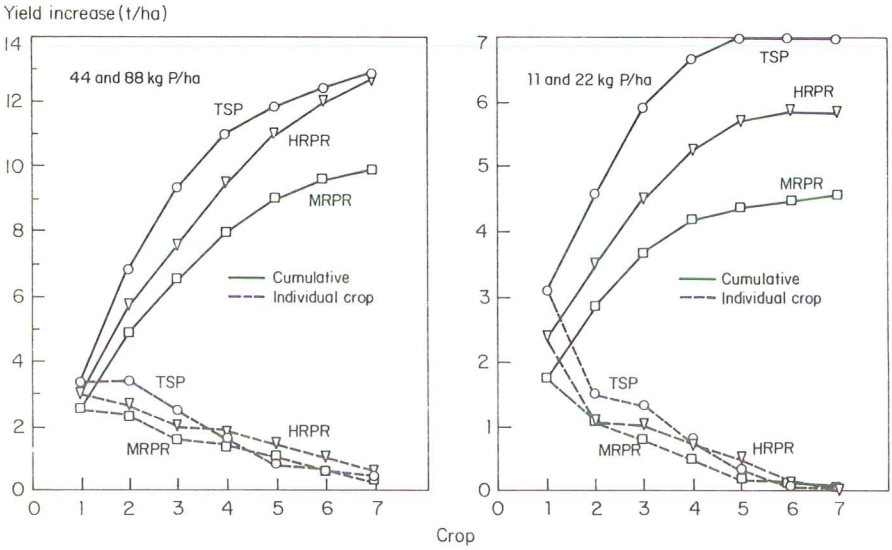
Phosphorus sources

There is no evidence of differences in rice response to various sources of water-soluble P. However, some P sources contain other nutrients that may or may not be suitable for wetland rice, notably nitric phosphates. In these fertilizers, N is present as NH_4^+ and NO_3^-. Surely, most of the NO_3^- would be lost if used as a basal dressing on soils that are or will become anaerobic. Other NP fertilizers generally contain N in the NH_4^+ form, which, recent results show, may be an advantage over urea if free water is on the soil surface at the time of incorporation. Potential NH_3 losses may be reduced because less fertilizer N enters floodwater from NH_4^+ salts than from urea.

Phosphate rock (PR) has been evaluated for rice in a number of locations by Mandal (29), Khasawneh and Doll (25), and Friesen and Blair (16). Two important principles must be borne in mind when testing PR: 1) PR from various deposits differs in reactivity and thus must be characterized, and 2) PR dissolution in soil increases with decreasing pH and Ca and P concentrations.

Chien (7) showed highly significant correlations between P concentrations in soil solutions and both citrate solubility and carbonate substitution within apatite structure among seven samples of PR incubated in an acid silt loam soil low in P and exchangeable Ca.

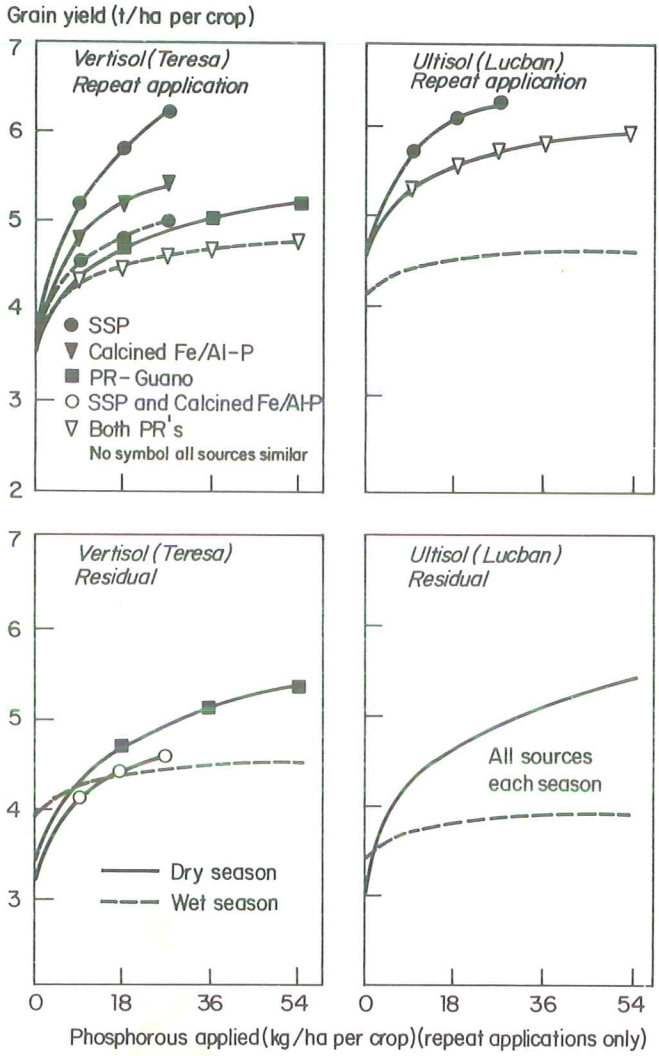
Engelstad et al (14) reported increased yield responses of rice grown on an acid sulfate soil in Thailand as the citrate solubility of the PR increased. During the first crop after application, all PR gave less response than triple superphosphate (TSP). Diamond (13), using yield data from seven crops from that experiment, illustrated that rice yields during the first three crops after P fertilization were less from PR than from TSP, but at high rates of application highly reactive PR was superior for crops 4 through 7 (Fig. 2). Thus, accumulated yields (seven crops) from superphosphate and highly reactive PR were equal, but yield from moderately reactive PR was less. At lower rates of application, significant response was obtained after crop 5, and accumulative yield increases were in the order TSP > highly reactive PR > medium reactive PR.



2. Accumulative and individual crop response of rice to single application of low and high rates of P sources in Thailand. TSP = triple superphosphate, HRPR = highly reactive phosphate rock, MRPR = moderately reactive phosphate rock.

Pichot et al (35) showed significant responses of rice in Madagascar to highly reactive PR for 8-9 years after application of more than 88 kg P/ha. During repeated applications for five crops in the Philippines, superphosphate gave superior response on both a Vertisol (pH 6.5) and an Ultisol (pH 5.0) compared with calcined Fe-Al phosphate on the Vertisol or moderately reactive PR on the Ultisol. During the following six crops (no additional P added), responses to residual P from low and high water-soluble P sources were similar (Fig. 3). Total yield responses to 90 kg P/ha (18 kg/ha per crop for five crops) during 11 crop seasons were 1) Ultisol -- 116, 89, and 94 kg rice/kg P from single superphosphate (SSP), moderately reactive PR, and local PR (guano), respectively, and 2) Vertisol -- 178, 140, and 135 kg rice/kg P from SSP, calcined Fe-Al P, and local PR (guano), respectively.

On a loamy Inceptisol (pH 5.3) and a Vertisol (pH 5.0), greater yield responses were obtained from SSP than from moderately reactive PR or from PAPR-15 (PR acidulated to 15% of requirement for SSP) (Diamond and De Datta). SSP and PAPR-30 (PR at 30% acidulation) gave similar yield responses at both sites. Yield responses to P exceeded 30% at both sites, and average agronomic efficiencies at 20 kg P/ha were 50 and 100 kg grain/kg P on the Inceptisol and the Vertisol, respectively. Responses to residual and fresh application of P were similar on the Vertisol during the 1983 wet season.



3. Irrigated rice yield responses to fertilizer P sources and the residual fertilizers (19).

Time of application

Farmers often delay fertilizer P applications because they know that basally applied P can stimulate weed growth, or, as is often the case, they may not have the fertilizer on time. IAEA (18) concluded from field experiments conducted in seven countries during 1962-63 that rice yield responses were little influenced by P application at transplanting, 2 weeks before PI, and halfway between. However, only one-half of the IAEA experiments showed any response to P. Moreover, the IAEA fertilization rate of 26 kg P/ha appears too high for there to have been P response differences no matter

what the time of application. Although time of application showed little effect upon yield, where P responses were obtained, 60-75% as much P in plants was derived from fertilizer applied 2 weeks before PI as when basally applied.

Patrick et al (34) reported that the average yield for five experiments (1964-69) was 400 kg/ha greater from 21 kg P/ha when drilled at seeding than when topdressed at 2-3 WT. The placement effect is unknown for this data. Patrick et al (34) found that the 3-year average yield decreased as topdressing of P was delayed for 2, 4, or 6 WS. In both series of experiments, the effect of delayed application of P was greatest when yield response to P was greatest.

Katyal (23) reported lower yield response to P from application at 7 DT than from a basal application in a dry season (>5 t/ha response to P) on a Vertisol in India. He found no significant yield differences for basal, and 7, 14, and 21 DT during the wet season (≅2.5 t/ha response to P). Later applications, up to 63 DT, resulted in lower yields.

In the Philippines, on a Vertisol (pH 6.8) and an Inceptisol (pH 5.6) where the maximum yield response to P of a short-duration variety of rice was 15%, no significant difference in yield response was found between times of application. Application times were before transplanting and 0, 14, 28, and 42 DT. In an experiment on an Inceptisol (pH 4.9) in which the maximum yield response was 32%, response was significantly less to P applied at 42 DT than to P applied at other times. Average agronomic efficiencies at 20 kg P/ha in the two former experiments were 20-30 kg rice/kg P and in the latter 40 kg rice/kg P. Responses to residual P were similar in fresh applications on both the Vertisol and the Inceptisol (pH 4.9) in the 1983 dry season.

Concerning time of application of fertilizer P within a cropping sequence, several authors advocate the addition of P to an upland crop that precedes rice or to the first rice crop following cool temperatures (4, 20, 33).

Application methods

Results of nine pot experiments from seven countries showed that surface application resulted in a greater percentage of fertilizer P in plants than did the mixing of P with soil (18). Follow-up field experiments showed that dry matter yield and percentage of P in plants derived from fertilizer were similar for the two methods of application. Placement of fertilizer P at 10- or 20-cm depth, either in planting hills or between rice rows, generally gave lower yields and percentages of fertilizer P in plants than surface-applied or soil-mixed P.

Recent results in the Philippines showed similar responses of a short-duration variety to basal applications of P, surface applied or mixed with soil, on each Vertisol, Alfisol, and Inceptisol (Diamond and De Datta).

Katyal (23) reported that dipping seedling roots into a slurry of superphosphate and soil before transplanting provided greater yield response than soil applications of similar rates of P on a P-deficient Vertisol. Lu et al (27) report that the method of dipping seedlings into P slurry is used in China and results in 40-60% more savings of fertilizer P than soil application of P.

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EFFECT AND MANAGEMENT OF POTASSIUM FERTILIZER ON WETLAND RICE IN CHINA

LIN BAO

According to the program of the National Network on Fertilizer Experiments (NNFE) since the late 1950s, a great number of field experiments had been conducted in different provinces in the rice-growing regions of southern China. To investigate the soil K status influencing fertilizer response, many representative soil samples from experimental sites were analyzed for K content. In the past 20 years, the role and response of K fertilization and techniques for using it efficiently have been recognized. This paper presents data on the proper use of K fertilizer in the wetland rice regions of China.

The results of NNFE field trials in 1958 and 1982 show the changing trend of fertilizer effects in China (Table 1)(2).

In the 1950s response to K was very limited. For example, in 62 field trials on the effect of NPK in wetland rice conducted in 1958, the highest response was to N, the next highest to P and the lowest to K. Twenty years later, the response to NPK fertilizers evidently changed because of the improvement of productive conditions and changes in soil fertility, as shown by the incremental increase in rice grain yield. The results of 260 trials in 1982 showed that the response to N fertilization obviously decreased. In

Table 1. Effect of NPK fertilizers on wetland rice in China.

Year	Trials (no.)	Trials showing marked response (%)			K response (yield in proportion to wt of each element applied)		
		N	P	K	N	P	K
1958	62	82	50	29	16.5	5.5	3.8
1982	260	95	50	63	10.1	3.5	5.8

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those areas where P fertilization has continued for many years, response to P decreased also, but the response to K increased gradually.

In the mid-1960s, symptoms of K deficiency in rice appeared in a large area of China. Recently, there have been indications that the K-deficient area is expanding (3). The reasons are the rapid increase in the rate of N and P fertilizers used on wetland rice, the limited use of K fertilizer, the wide adoption of high yielding rice varieties and hybrids, and the significant rise in the multiple cropping index and yield. A large amount of K is taken up from the soil. The K supplied by organic manures cannot meet the needs of high yielding rice, and soil K is gradually depleted (4).

The effect of K fertilization is very significant in K-deficient soils. First, K promotes the growth of the root system of rice. Investigations of the Soil and Fertilizer Research Institute of Zhejiang Province showed that 6 days after transplanting there were twice as many roots per hill and 62% more new roots in the treatment with K fertilizer than in that without. Decayed roots were 79% fewer than in the control. Potassium fertilization also accelerates the growth of stems and leaves. With K application, tillering is earlier, rice shoots are vigorous and stronger, and premature plant senescence does not occur. Potassium fertilization in Zhejiang, Hunan, and Guangdong Provinces increased the number of panicles per hectare by 150,000-300,000, increased filled grains by 5-15%, filled grains per panicle by 5-20 grains, and 1000-grain weight by 0.5-4.0 g. It also increased the percentage of milled rice by 1-3%.

Also, K fertilization can prevent and reduce the occurrence and extent of some physiological disorders and parasitic diseases such as brown spot, sheath blight, and rice blast (3).

FACTORS INFLUENCING RESPONSE TO K AND EFFICIENT USE OF K FERTILIZER

Many factors -- mainly the K-supplying power of soils, application rate of N and P fertilizers, the type and amount of organic manures, the type and variety of rice and its K requirement -- influence the effect of K. To achieve the high response and economic returns of K fertilization, K must be supplied reasonably and used according to the factors that influence the crop's response to K.

Soil K-supplying power

Soil K can be divided into three fractions: available K, slowly available K, and mineral K. The K response of growing crops depends mainly on the availability of

soluble and exchangeable K, and to a lesser extent on the content and release rate of slowly available soil K. In successive rice cropping without supplemental K, a greater portion of K is afforded by slowly available K. In the short term, mineral K makes little contribution to the crop (9).

The contents of soil-available and slowly available K vary with the type and fertility of soils. The relation between soil K content and K response in rice-growing regions of South China is shown in Table 2. Four grades of soil K-supplying power can be classified according to the content of available K and slowly available K.

The K-supplying power of the soil is the main factor that determines whether K fertilization gives a significant response. In South China the temperature and rainfall are high. The weathering and leaching process of soil is comparatively strong. In addition, tillage and cropping are intensive, and K loss and exhaustion are high. Therefore the soil K content of southern provinces is generally lower than in other regions in the country.

According to a survey of the Institute of Soil Science, Academia Sinica, the status of soil K in rice-growing regions is generally as follows (1).

The lateritic soils (latosol) derived from basalt and marine deposits, and the lateritic red earth derived from granite and gneiss in Guangdong and Fujian provinces and in the Guangxi Zhuang Autonomous Region of South China contain <4% K-bearing minerals, 0.2-0.4% total K, and 40-100 ppm slowly available K. These soils have the lowest K content in China, and paddy soils developed on them are highly deficient in K. Red earth derived from limestone in Guangxi and Yunan containing about 0.3% K and 30-170 ppm slowly available K is another highly K-deficient soil.

Table 2. Relation between soil K content and response to K fertilization.

Available K[a] (ppm)	Slowly available[b] (ppm)	Soil K-supplying power	Incremental yield response to K (%)
<50	<200	Very low	Increment of yield very significant
50-100	200-300	Low	Increment of yield significant
100-150	300-400	Medium	Increment of yield observable but not steady
>150	>400	High	No response

[a]By 1 N NH_4Ac extraction. [b]By boiling in 1 N HNO_3 for 10 min from which the content of exchangeable and water-soluble K is subtracted.

Red earths derived from Tertiary red sandstone and Quaternary red clay are widely distributed on the hilly land of Central China (Hunan, Hubei, Jiangxi, and other provinces). They contain about 10% K-bearing minerals, <1% total K, and about 200 ppm slowly available K. Red earths occurring on the lower slopes of gentle hill land are mostly terraced and used for rice and other crops. There are various types of cold, muddy paddy soils with excess water in this region. They have sandy texture and are strongly reduced. Rice response to K fertilizer in these low-yielding fields is especially high.

There are large areas of alluvial soils in the region of the middle and lower reaches of the Yangtse River in Central China. The K content of these lacustrine soils is medium: around 2% total K and 300-500 ppm slowly available K. These soils are used mainly for rice. The sandy soil derived from the river deposits is deficient in K. Because of the intensive cropping system and the large amount of manure applied over time, no response to fertilizer was observed in the past, but in recent years response to K fertilizer has begun to show.

Purplish soils derived from purplish sandstone and shale are distributed mainly in Southwest China. They contain a total of about 2.5% K and 500-700 ppm slowly available K. They have the highest K content among soils of South China.

Effect of NP fertilizers on N-P-K ratio

Field trials conducted in Guangdong and Zhejiang provinces showed that response to N fertilizer is highest when NPK fertilizers are applied. Increasing the rate of N without a corresponding increase in K reduces the effect of N fertilizer. The effect of K fertilizer increases with increasing rate of N fertilization (Table 3). At higher levels of N fertilizer, the effect of K fertilizer is raised by 11-50% in Guangdong and by 35-39% in Zhejiang.

Crop response to K fertilizer is higher when K is combined with N and P than when it is combined with N alone (Table 4).

In the rice regions of South China, the suitable ratio of NPK without manure is 1:0.5:0.4, and 1:0.3:0.3 with manure. In Guangdong and Guangxi, the proportion of K should be higher. The suitable N-K ratio should be adjusted to 1:0.4-0.5. Presently it is 1:0.13-0.2. In the region of the middle and lower reaches of the Yangtse River, the proportion of K to N could be a little lower, about 1:0.2-0.3. At these ratios, NPK fertilizers could be more effective in increasing rice yields.

Also, K fertilizer should be used early and in amounts that give maximum returns. Trials in China show

Table 3. Influence of N fertilizer rate on effect of K fertilizer.

Province	Treatment	N:K	Rice yield (t/ha)	Incremental yield increase		Effect of K at different rates of N (%)
				(%)	(t/ha)	
	$N_{30}K_0$	1:0	4.0	–	–	
	$N_{60}K_0$	1:0	4.5	–	–	
	$N_{90}K_0$	1:0	4.5	–	–	
	$N_{30}K_{56}$	1:1.9	4.7	15.2	0.6	100
Guangdong	$N_{60}K_{56}$	1:0.9	5.2	16.1	0.7	116
	$N_{90}K_{56}$	1:0.6	5.2	15.2	0.7	111
	$N_{30}K_{112}$	1:3.8	4.7	14.7	0.6	100
	$N_{60}K_{112}$	1:1.8	5.2	16.1	0.7	120
	$N_{90}K_{112}$	1:1.2	6.5	19.8	0.9	150
	$N_{60}K_0$	1:0	3.37	–	–	
	$N_{120}K_0$	1:0	3.02	–	–	
Zhejiang	$N_{60}K_{56}$	1:0.9	4.83	43.3	1.46	100
	$N_{120}K_{56}$	1:0.5	4.99	65.2	1.97	135
	$N_{60}K_{112}$	1:1.8	5.23	55.2	1.86	100
	$N_{120}K_{112}$	1:0.9	5.60	85.4	2.58	139

Table 4. Effect of K fertilizer combined with N and P fertilizers.

Province	Treatment	Rice yield (t/ha)	Incremental yield increase with K fertilization	
			(t/ha)	(%)
	N	5.0	–	–
	NK	5.3	0.28	5.6
Hunan	NP	5.2	–	–
	NPK	5.7	0.46	8.8
	N	3.7	–	–
	NK	4.2	0.42	11.1
Guangdong	NP	3.9	–	–
	NPK	4.6	0.71	18.4
	N	4.2	–	–
	NK	4.6	0.33	7.7
Zhejiang	NP	4.4	–	–
	NPK	5.0	0.65	14.7

that the approximate K uptake at different stages of rice plant growth is 0.4% of total K uptake at the seedling stage, 17-29% at tillering, 50-60% at booting, and 10-20% from heading to ripening. Inasmuch as the rice plant begins to take up more and more K from tillering to booting, it is better to apply K fertilizer basally or topdressed before maximum tillering.

In view of the present K content in soil and of the rice yields in South China, the maximum economic returns from K application can be obtained at the rate

of 29-62 kg K/ha. When K fertilizer is insufficient, topdressing the rice seedling bed can notably improve the quality of seedlings, which turn green faster after transplanting. Moreover, a yield increase of 3-5% may be obtained with no further K added (3).

Relation between the use of organic manure and K fertilizer

The use of organic manure is traditional with Chinese farmers. Organic manure also influences the effect of K fertilization on rice. The use of organic manure and straw can decrease the need for K fertilizer to some extent and ameliorate soil K deficiency. Most organic manures for rice are applied basally. Leguminous green manure is rich in N; compost and barnyard manure are rich in K. In experiments in Zhejiang Province, K fertilization combined with N and P fertilizers gave the highest incremental rice grain yield of 16.9%. The effect of K fertilizer combined with green manure is a little less, an incremental increase of 11.4%. The incremental yield increase of K fertilizer used in combination with good-quality manure as a basal treatment is comparatively low, 5.5%. The response of rice to K fertilization decreases with increasing manure application.

The K content of rice straw is high, and K-deficiency symptoms of rice can be decreased and the yield increased by returning the rice straw to the soil (8).

K responses of various rice types and varieties

Modern varieties and sinica rice generally take up more K than the indica rice commonly cultivated. Therefore, they are rather sensitive to K application and their response to K fertilizer is relatively high. Moreover, hybrid rice takes up much more K than the common sinica rice and is even more sensitive to K application, responding to K addition with even higher incremental yields (6). This has been verified by the trials in Huangjin People's Commune, Wangcheng County, Hunan Province, during the late 1970s and the early 1980s (Table 5).

Table 5. Effect of K application upon the yield increase for different rice types and varieties.

Rice type	Trials (no.)	Yield (t/ha)		Incremental yield increase		Response to K (kg)
		Without K	With K	t/ha	%	
Indica	48	4.2	4.7	0.5	11	5.25
Sinica	2	4.6	5.4	0.8	17	8.00
Hybrid rice	5	4.7	5.6	0.9	19	9.50

Under the common conditions of cultivation, tall-stemmed indica rice straw contains 1% K, short-stemmed indica rice straw about 2%, and hybrid rice straw about 2.8% (7). There is no significant variation of K content in the grains, about 0.5% in all the three rice types. To produce 1 t rough rice, a straight-line rice variety takes 21 kg K, but hybrid rice requires 35-43 kg K. Hybrid rice Nanyou-2 took in 308 kg K when 9.86 t rough rice/ha was produced. It continued to take up K after full heading. The K uptake after heading amounted to 19.2% of total K uptake.

The effect of K in relation to the multiple cropping index and cropping system

A triple cropping system such as early rice - late rice - winter crop depletes soil fertility rapidly. Shanghai Municipal Bureau of Agriculture statistics for 1975-1979 showed that the yield of a triple cropping system was 4 t/ha more than that of a double cropping system of late rice - winter crop. The uptake of NPK obviously increased, and K uptake was especially high, 110 kg K/ha per year. Therefore the effect of adding K fertilizer under conditions of intense cropping would be outstanding (4).

A rice - rice - green manure cropping system has been practiced for a long time in up to 60% of the rice fields in some southern provinces of China. In these rice fields in which green manure is used as a basal dressing, only a small amount of other organic manure is added. Consequently there is no appropriate K supplement added. The fields with green manure are not plowed up in winter, and the subsoil is not exposed to the open air. In these cases, the potential K cannot be realized fully. The reduced condition of the soil after incorporation of green manure hinders the rice roots from taking up K. In those fields where a rice green manure rotation has been practiced for a long time, K fertilizer shows a marked effect on yield increase (5).

The effect of K fertilizer shows most in the season during which it is applied. When K fertilizer is sufficient, yields are higher if it is applied to each crop in the triple cropping system. When K deficiency exists, applying K to late rice gives a better effect than applying it to early rice in the double cropping system. The main reason for this is that less organic manure is applied to late rice. In a cropping system, including rice - rice - green manure, K fertilizer should be applied to legumes to facilitate their growth. Then the leguminous green manure is plowed under as a basal fertilizer for early rice (3).

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AVAILABILITY AND MANAGEMENT OF POTASSIUM IN WETLAND RICE SOILS

H. R. VON UEXKULL

Potassium use in tropical wetland soils is still in its infancy. In the past, when yields were low, most soils could supply sufficient K to maintain yields. The lack of response of crop plants to K in most early experiments has diverted the interest of soil fertility researchers to other subjects. As a result, the available information on K management in wetland soils is meager compared with information available on nitrogen. Most wetland rice soils are in a state of rapid fertility change, making the selection of correct rates of K application difficult. Proper timing and placement of K are important on some soils, but appear to be of little significance on soils having a high CEC. Potassium interacts with many nutrients, N, P, and S in particular. Experience in many countries, particularly China and Indonesia, has shown that continued use of N depletes soil K and sharply reduces the efficiency of fertilizer N.

Although China was probably the first country to make systematic use of plant ashes, the history of chemical potash fertilizers in Asia is rather short. Fertilizer use in most of Asia followed a different pattern from that in Europe or North America.

In Europe and North America, the first chemical fertilizers used were P and K. Nitrogen consumption started to catch up with P and K consumption only in the 1960s when the introduction of centrifugal compressors led to single stream ammonia plants that could produce cheap nitrogen.

In Asia, with the exception of Japan, large-scale fertilizer use started with N, and K needs have only slowly been recognized as a result of yield increases obtained from the use of N in combination with high yielding, modern varieties (MVs), which were developed at about the same time the new ammonia technology emerged.

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Traditional agriculture in Europe was largely based on leguminous forage crops grown in rotation with root and cereal crops. Potassium and P fitted perfectly into such system as they helped stimulate biological N fixation.

By contrast, in most rice-growing regions, there was very little room for legumes in the rotation with the exception of Chinese milk vetch and N was the primary nutritional constraint to increased yields. The need for K is now developing largely because of the rapid increase in the use of N and the resulting increase in K uptake and removal.

In Europe, the build-up of soil P and K helped to create conditions favorable for increased use of N, whereas in rice-growing Asia, yield increases due to heavy application of N are draining reserves of soil K, making K application an eventual necessity in stabilizing high yields.

POTASSIUM IN TRADITIONAL RICE CULTURE

Most of the early fertilizer work indicated that lack of K was not a constraint to rice production. For India, Sethi et al (21) stated, "...since none of the experiments in any part of India has indicated any effect, beneficial or harmful, by the application of potassium, it has been left out of the discussion." Similar conclusions were reached by researchers in many other countries (1). Grist (8) warned, "Some evidence exists that where there is no lack of potash, further additions may have a small negative effect on yields and therefore the inclusion in fertilizer mixtures is not warranted merely on an insurance or balancing principle unless it is demonstrably in deficit."

Except in a few, insignificant locations, there was indeed no need for K in traditional, low-yielding rice culture. Before the introduction of nitrogen-responsive MVs, even the response to N was relatively small and the response curve tended to bend down at N input levels of 20-40 kg N/ha.

Until the release of modern indica-type varieties in the mid-1960s, high fertilizer inputs (including K) and high yields were limited to East Asia, principally Japan, Korea, and Taiwan, China.

In tropical Asia, yields were low and in many cases the straw was left on the field. In that situation even poor soils were not stressed for K.

IMPACT OF THE MVs

The impact of the MVs is best illustrated by the trends in N consumption and in rice production in Indonesia. From 1960 to 1966, rice production stagnated between 9

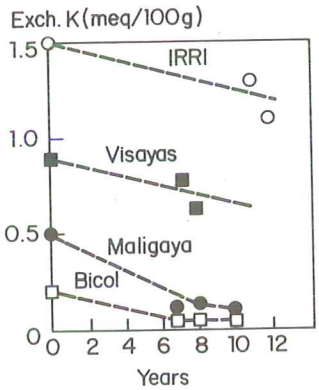
and 10 million t. Beginning in 1968, there was a steep increase in N consumption and in rice yields. By 1980 Indonesian rice production had surpassed the 20 million level, and N consumption had risen by 14 times, from 50,000 t in 1960 to 720,000 t in 1980. Though no figures are available, it can be assumed (assuming an absorption of 21.6 kg K/t paddy) that as a result of this yield increase, the total K uptake of Indonesia's rice crop increased from 1.9 million t in 1964 to at least 4.8 million t in 1980.

Beyond the effect of a high yield per crop, the photoperiod-insensitive MVs often had a shorter growing period than traditional varieties and could be planted at any time of the year, permitting farmers to grow two or more crops per year where only one crop had been grown before.

To monitor changes in the capacities of rice soils to supply NPK over a period of intensive cropping, the International Rice Research Institute (IRRI) conducted long-term trials at three stations of the Philippine Bureau of Plant Industry. In their report covering the first 10 consecutive cropping seasons, De Datta and Gomez (4) observed a decline in the efficiency of N applied alone at all locations, and a marked increase in the response to K over time.

On the basis of the data provided by De Datta (3), Kemmler (12) reported changes in exchangeable soil K (Fig. 1). Using data from the Philippines, von Uexkull (26) calculated the nutrient balance under different fertilizer treatments over a 5-year period, as shown in Table 1.

Another factor that is leading to a more rapid depletion of the natural K reserves of many wetland soils is the increased use of rice straw as a source of fuel and industrial raw material. In Bangladesh, for example, in some areas there is such a shortage of fuel wood that farmers plow up the rice stubble and roots



	Av yield NP plots (t/ha)	Response to K (t/ha)
IRRI	7.2	0.0
Visayas	5.6	0.4
Maligaya	5.2	0.9
Bicol	5.0	1.9

1. Change in soil K status at four sites of long-term NPK experiments in the Philippines.

for use as cooking fuel. A similar situation exists in parts of China. Although part of the K may be returned to the soil with the ashes, burning the straw results in increased K losses and a less even distribution or redistribution of K.

As a result of the introduction of MVs the rapid increase in the use of N fertilizers and the increasing use of rice straw as a fuel, most wetland rice soils are undergoing rapid dynamic changes in their K supply status (Table 1). An increasing area of wetland rice soils will become K deficient unless countermeasures are taken.

POTASSIUM IN WETLAND RICE SOILS

Most wetland rice soils are undergoing rapid dynamic changes. To take stock of their K status under the present situation is like taking a still picture of a rapidly moving object.

Kawaguchi and Kyuma (10) and Moormann and van Breemen (16) have provided a great deal of information on the current fertility of wetland rice soils and Kemmler (11, 12) has provided two excellent reviews on their K status. Table 2 summarizes Kawaguchi and Kyuma's survey data. Among the countries surveyed, Sri Lanka had the highest percentage (58) of soils inherently low in K (below 0.15 meq K/100 g) and Philippine soils had the highest average K content, with only 15% of the soils analyzed measuring below 0.15 meq K/100 g.

Potassium is present in soils in four forms, which are in dynamic equilibrium (23):

K in soil solution (instantly available K)	Exchangeable K (easily mobilizable reserve of K)	Nonexchangeable (slowly mobilizable stock of K)	K in soil minerals (semipermanent K) reserve)

For fast-growing plants, the intensity of K supply, which depends largely on the concentration of K in the soil solution, is of primary importance. Flooding enhances the release of K from nonexchangeable and exchangeable forms into the soil solution (2, 20, 26).

This means that flooding helps mobilize soil K to sustain plant growth. But it also means that under intensive cropping, available soil K reserves can be exhausted much faster.

MANAGEMENT OF POTASSIUM FERTILIZER

Because K cannot be lost through volatilization or change into another gaseous form like N (denitrification), it is generally assumed that its management is simpler than that of N (3).

Table 1. Calculated nutrient balance under traditional culture compared with high-yield culture under double cropping and different fertilizer treatment for a 5-year period.

Treatment	Total grain yield in 5 yr[a] (t/ha)	Nutrient absorbed and removed with the grain + straw[b] (kg/ha)			Nutrients added[c] (kg/ha)			Balance[d] (kg/ha)		
		N	P	K	N	P	K	N	P	K
					Traditional culture					
	7.5	126	29	164	–	–		−126	− 29	− 164
					MV culture (double cropping)					
No fertilizer	32.4	545	124	710	–	–	–	−545	−124	− 710
N	50.1	840	192	1097	1050	–	–	+210	−192	−1097
NP	54.7	920	210	1198	1050	264	–	+130	+ 54	−1198
NPK	59.3	995	227	1299	1050	264	498	+ 55	+ 37	− 801

[a]Traditional culture = 5 crops, MV/culture = 5 dry-season and 5 wet-season crops. [b]Assumes that for every tonne of grain 16.8 kg N, 3.83 kg P, and 21.9 kg K are removed with the grain and straw. Removal figures will not be the same for all treatments, the figures presented should be read to indicate the trend rather than to be taken as absolute value. [c]26.4 kg P and 49.8 K per crop, 140 kg N for the dry-season crop, and 70 kg N for the wet-season crop. [d]Excludes losses due to leaching and additions of nutrients through irrigation water.

Table 2. Exchangeable K in paddy soils of some Asian countries.

Country	Samples (no.)	Exchangeable K (meq/100 g)			
		Mean exch.	SD	Min	Max
Bangladesh	53	0.3	0.2	trace	0.8
Burma	16	0.4	0.2	0.1	0.7
Cambodia	16	0.2	0.2	trace	0.8
Indonesia	44	0.4	0.3	0.1	1.2
W. Malaysia	41	0.4	0.4	0.1	1.8
Philippines	54	0.5	0.3	0.1	1.7
Sri Lanka	33	0.2	0.2	trace	0.7
Thailand	80	0.3	0.4	trace	2.6
Total mean	337	0.35	0.28	0.1	1.29
India	73	0.5	0.4	0.1	2.3
Japan	84	0.4	0.3	trace	1.4

This is true as far as management techniques to avoid losses are concerned. On the other hand, the number of experiments involving management of K fertilizer is only a small fraction of those carried out with N. Responses of rice to applied K are often erratic and inconsistent, and few answers are available to explain such erratic patterns.

POTASSIUM SOURCES

About 95% of the world's K fertilizer supply is in the form of potassium chloride, the only K fertilizer source of significance for rice, either alone or in NPK compounds or mixtures.

POTASSIUM RATES

Selecting the correct rates of K application is currently the most problematical aspect of K fertilizer management. As explained earlier, most wetland rice soils are undergoing rapid, dynamic changes in fertility. Soils that may not be responsive to K today may require 20 kg K/ha next year and 75 kg K/ha a few years later to maintain the same yield. Present methods of plant and soil analysis lack precision, especially for soils of different geological origin. Once a soil is known to be responsive to K, the optimum rate of K application will eventually become largely a function of the targeted yield level and the rate of N to be used. For finer tuning, one would have to know the constant rate at which K can be released without changing the K status of the soil, the amount of K contributed through the irrigation water, and the amount of K recycled with the straw. Assuming that rice has to absorb K at 22 kg/t paddy produced, K rates can be calculated as shown in Table 3.

Table 3. Calculated K fertilizer requirement for various rice yield levels assuming a constant K supply from soil and irrigation water.

Yield (t/ha)	Crop K requirement (kg/ha[a])	Constant K supply (kg/ha)		Total supply (kg/ha)	Balance (kg/ha)	K needed[c] (kg/ha)
		From soil	From irrigation water[b]			
2	44	50	20	70	+25	–
3	66	50	20	70	+ 4	–
4	88	50	20	70	-18	30
5	110	50	20	70	-40	67
6	132	50	20	70	-62	103
7	154	50	20	70	-84	140
8	176	50	20	70	-106	177

[a]Assuming 22 kg K absorbed/t paddy. [b]Assuming 2 ppm K/1000 mm water. [c]Assuming 60% utilization of applied K.

Experience has shown that responses to K fertilizer are often inconsistent. In India, responses to K were good on soils with a high K status (14). On the other hand, low or no response was observed on soils low in available K (6).

In another 3-year trial in India, there was a good response to 25 kg K/ha the first year, a reduced response to 50 kg K/ha the second year, and a markedly increased response to 75 kg K/ha in the third year, even higher than the response to the rate of 25 kg K/ha in the first year.

During a transitional period, responsive soils respond very well to rather low rates of K (25 kg K/ha), probably because of a rapid recharge of K on the exchange sites from nonexchangeable K sources. This could be considered a priming effect. Once the pool of exchangeable and nonexchangeable K is exhausted, high rates of K are needed to maintain high yields.

To make better use of soil analysis in estimating K fertilizer needs, methods must be developed that provide more information on the slowly available K fraction in the soil in addition to exchangeable K. Dynamic methods such as electro-ultra filtration (EUF) (17) and methods using HNO_3 as an extractant deserve more attention.

TIMING AND PLACEMENT OF POTASSIUM

Timing

Most textbooks recommend a basal application of K and P at the time of the last land preparation. Such standard techniques have been adopted from upland cereals grown under upland conditions, entirely different from those found under wetland conditions.

Timing of K application for rice is still a controversial issue, but there is ample evidence that for paddy a split application or topdressing is often superior to a simple basal application. Farmers in Japan were probably the first to discover this.

The best time for topdressing is about 35-40 days before heading (15). Yamasaki (29) showed that on a deficient soil, K applied as a basal dressing increased straw yield by 29%, but had no effect on grain yield. Applied in three split dosages, the same amount of K was less effective in increasing straw yield (23% increase), but increased the rice yield by 19%. Similar results have been reported from many other countries (5, 22).

Ismunadji and von Uexkull (9) tested the effect of timing of K application on the efficiency of applied K in Indonesia. The greatest yield response was achieved when a single dose was applied at maximum tillering (Table 4).

On high-CEC soils in the Philippines, split applications of K gave no advantage over a single dose (4). Problems related to timing of K have been reviewed by von Uexkull (25, 27).

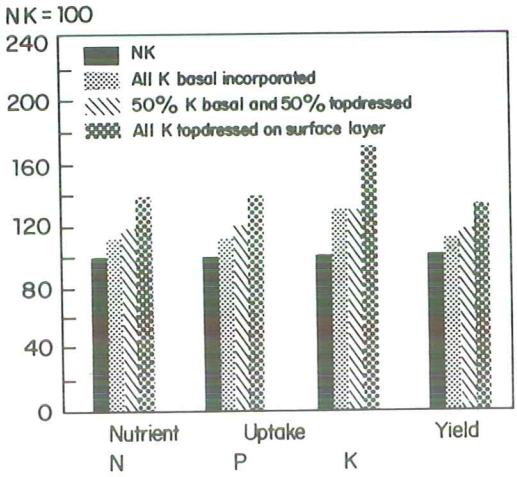
PLACEMENT

The standard recommendation calls for incorporation of K into the soil at land preparation. It appears, however, that on poorly drained soils in which K uptake from lower soil strata is a problem, surface applications of K in several split doses can be effective. Kim and Park (13) observed that rice plants grown on a poorly drained, heavy acid sulfate soil in a coastal plain in Korea were low in K inspite of a high K content in the soil. Potassium incorporated into the soil before transplanting gave only a small, insignificant yield increase. The same amount of K applied to the oxidized surface layer gave a highly significant yield increase (Fig. 2).

Table 4. The effect of timing on the efficiency of applied potassium in Indonesia (9).

K treatment[a] (kg/ha)	Grain yield (t/ha)	Yield increase over control (kg/ha)	K efficiency (kg grain/ (kg K)
No K	4.2	–	–
66 kg basal	4.9	684	10.4
66 kg at maximum tillering	5.8	1597	23.1
33 kg at maximum tillering and 33 kg at panicle initiation	5.3	1056	15.9
33 kg as basal and 33 kg at panicle initiation	5.0	874	13.1

[a] N = 120 kg/ha, 50% basal and 50% at panicle initiation; P = 26 kg/ha basal.



2. Effect of timing and placement of K on yield and nutrient uptake of rice (13).

Existing data are insufficient for general rules on the timing and placement of K, but preliminary guidelines can be given.

Emphasis on basal application

- Heavy-tillering varieties or close spacing, or both.
- Varieties tolerant of iron toxicity.
- Early-maturing varieties.
- High-CEC soils.
- Initial irrigation water low in K.
- Light soils inherently low in K (at low levels of K application).
- Calcareous soils or irrigation water high in HCO_3.
- Poorly drained soils.
- Dry-season crops.

Emphasis on split application or topdressing only

- Medium- to low-tillering varieties.
- Varieties sensitive to phosphorus deficiency and iron toxicity.
- Late-maturing varieties.
- Wide spacing.
- Soils where the EH tends to reach high levels.
- Light soils (at high levels of K application).
- Acid-sulfate soils.
- Alkaline soils, high in organic matter and deficient in Zn.
- Soils low in P or P-fixing soils.
- Wet-season crops.

INTERACTIONS WITH OTHER NUTRIENTS

Nitrogen

The interactions of K with N in paddy rice appear to be complex and little researched. Normally, one would expect that the efficiency of applied K would increase with N rate. There are, however, a number of cases in which K applied alone or in combination with P gave a small, yet significant, response but heavy rates of N caused the response to disappear (28). More research is needed on the timing of N and K applications to optimize their efficiency.

Phosphorus

De Datta and Gomez (4) showed that on deficient soils the efficiency of P depended heavily on the presence of adequate K, and vice versa. Application of K can depress yield when P is lacking, but can effectively increase yield when P is not limiting to yield.

Zinc

Soil conditions leading to Zn deficiency are also conducive to K deficiency. Adequate K can improve the oxidation power of the roots and in the process improve uptake of Zn.

Iron

Iron toxicity can be reduced or sometimes prevented by dressings of K (24).

Silicon

Application of silica slag or other Si sources such as Wallesbronite to soils low in available Si and low in K has often greatly improved the efficiency of applied K (18).

VARIETAL DIFFERENCES IN K RESPONSE

There are indications that varieties differ considerably in their K requirement and in their response to applied K. Tong-il in Korea and hybrid rice in China require substantially more K than ordinary varieties. Lack of a more general response to K in the past has prevented more research in this field.

DISCUSSION

Proper management of K in wetland conditions appears far more complex than management of K for upland crops. Research is lacking, especially in the field of timing,

interactions with other nutrients, and varietal differences in response to K. The role of irrigation water, both as a source of K supply and a source of K loss has not been researched sufficiently. For reasons not yet fully understood, responses to rates, timing, and placement are often erratic. Potassium interacts with many nutrients. The effect of applied K on rice yield can be direct or indirect by alleviating Fe toxicity or Zn deficiency or by reducing the susceptibility of the rice plants to disease. In most rice-growing countries of Asia, N use is increasing at a rapid rate, and now many rice soils that were unresponsive to K in the past are deficient in K, sometimes to the extent that applied N becomes ineffective. Changes in soil fertility as a result of modern, high yield technology have to be closely monitored to prevent yield decreases and wasteful use of N fertilizer.

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ZINC, SULFUR, AND OTHER MICRONUTRIENTS IN WETLAND SOILS

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Micronutrients are involved in the entire metabolic enzyme system of plants. The range between toxic and deficient levels is often very small; thus, the proper supply of micronutrients is essential for good plant growth. The electrochemical and biochemical changes caused by submergence directly and indirectly influence the solubility and availability of micronutrients in the soil. Submergence increases the availability of Fe, Mn, and Mo but depresses toxicities of Mn and Fe in acid soils. The availability of S, Zn, and Cu decreases with submergence. Little is known about the kinetics of B in flooded soils, but adsorption and occlusion to sesquioxides should be lower. Differences in response to micronutrients among rice varieties offer scientists the opportunity to overcome deficiency and toxicity problems with minimal, or even without, amendments.

Rice is grown as a wetland crop under diverse soil and climatic conditions, and all orders of Soil taxonomy (38) are represented in wetland rice soils. Thus, rice soils display a great deal of heterogeneity with respect to total and available micronutrients.

The electrochemical and biochemical events in submerged soils, such as reduction, changes in pH and CO_2 partial pressure, production of a wealth of fermentation products and humic substances, and resulting ionic interactions, all control the micronutrient regime of the rice crop. The net effect on rice may be deficiency or toxicity of a particular micronutrient. The susceptibility of rice varieties to micronutrient stresses displays wide genetic variability. For example in the last 15 years IRRI has screened about 120,000 rices for soil stresses and has found about 20,000 varieties tolerant of particular stresses.

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Ionic interactions in the soil and soil solution or metabolic interactions in the plant induce deficiencies or toxicities in rice. Accordingly, soil-plant relationships affecting the micronutrient nutrition of rice should be researched. Special emphasis should be given to Zn and S. Aside from lack of N, Zn deficiency is the most widespread nutrient disorder in all rice-growing regions of the world. In Asia, S deficiency in wetland rice has been recognized in Bangladesh, Burma, India, Indonesia, Japan, the Philippines, and Sri Lanka (1). During the past decades, S deficiency has assumed increasing importance as a growth-limiting factor for both dryland crops and wetland rice.

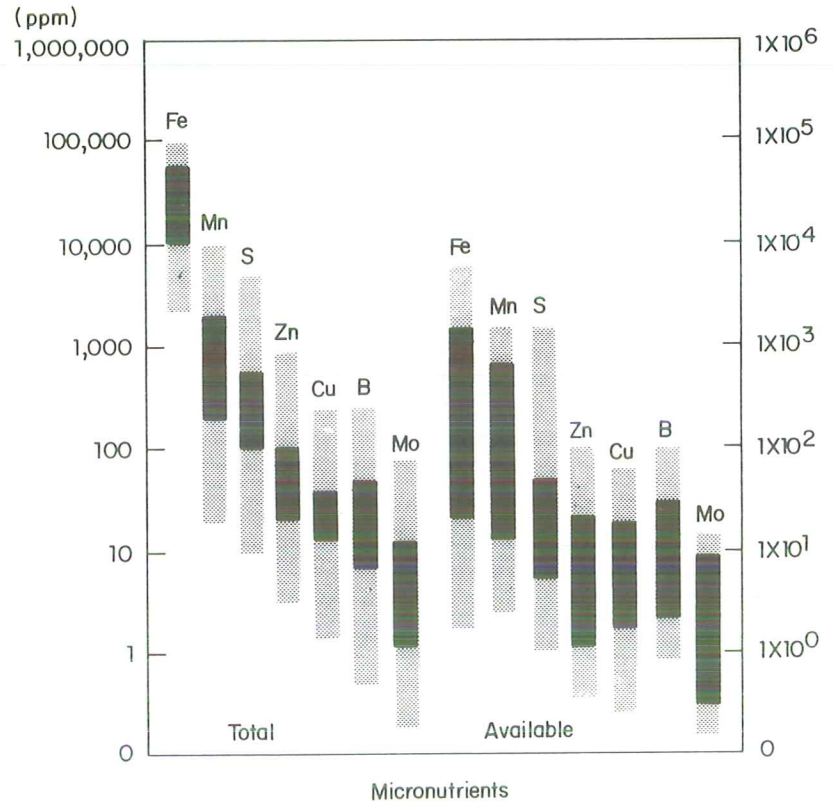
The amounts of the micronutrients B, Cu, Mo, Fe, Mn, Zn, and S in soils range from the fourth most abundant element Fe to the scarce element Mo. The four divalent micronutrient cations Fe^{2+}, Mn^{2+}, Zn^{2+}, and Cu^{2+} are similar in size, but their differences in ionic bonding are such that only Fe^{2+} and Mn^{2+} substitute extensively for one another. The small size of Mo^{6+} and B^{3+} together with their high charge and their tendency to form covalent bonds, results in their principal occurrence as oxyanions. Sulfur is present in the soil as the anions SO_4^{2-}, HS^-, and S^{2-}. Differences in electronegativity, ionization potential, ionic radii, and reduction potential lead to differential solubilities and behavior in submerged soils.

Figure 1 gives the range of total and available micronutrients in wetland soils. Availability is determined by several interacting factors such as pH, Eh, organic matter content, clay content, presence of carbonates and partial pressure of CO_2, salinity, and the quality as well as the biochemistry of the floodwater. In addition there are synergistic and antagonistic reactions to uptake and to metabolism in the plant. The most significant factors correlated with micronutrient availability are the electrochemical changes induced by submergence.

IRON

The reduction of Fe is a consequence of anaerobic metabolism (23). Within a few weeks of submergence 5-50% of active Fe(III) present in a soil may be reduced to Fe^{2+}, depending on microbial activity (temperature, organic matter), NO_3^- content, and crystallinity of the Fe oxides.

Acid soils high in organic matter and Fe may build up concentrations of more than 1000 mg/litre Fe^{2+}, but in calcareous soils the concentration could be less than 20 mg/litre.



1. The total and available micronutrients in rice soils. The dotted areas show unusual values.

The increase in concentration of water-soluble Fe following submergence can be described by the equation (28):

$$Eh = 1.06 - 0.059 \log Fe^{2+} - 0.177\ pH$$

or

$$pE = 17.97 + pFe - 3\ pH$$

According to this equation, at pE = -0.76 or Eh = -45 mV and pH 7 the toxic concentration of 300 mg/litre is reached, while at pE = 2.0 or Eh = +118 mV at the same pH a deficient concentration of 0.5 mg/litre exists. At pH 5 a redox potential of only +309 mV is needed to get a toxic level of 300 mg/litre. More detailed information about the kinetics of Fe is given in other papers in this volume.

The reduction of Fe releases other trace elements sorbed on and occluded in it (10) and displaces bases from the exchange sites. The toxic level of water-soluble Fe is thought to be >300 mg/litre. But Fe toxicity of rice plants is often related to a multiple nutritional soil stress (insufficient supply of K, P,

and Zn and sometimes Ca and Mg) rather than to a high level of active Fe (24). Iron toxicity occurs in strongly acid soils, particularly acid sulfate soils. It is often observed in poorly drained depressions or plains getting lateral or upwelling Fe-containing water.

Iron toxicity can be corrected by liming, drainage, prolonged submergence, and adding MnO_2, which acts as an antagonist to Fe in plant metabolism. Though organic matter amendments hasten the reduction and favor the early buildup of Fe in flooded soils, they decrease the water-soluble Fe thereafter because of increased pH. If the organic matter amendment is combined with the right timing of transplanting, it is a method of reclamation, but varietal tolerance may be the simpler remedy.

Iron deficiency is the most important nutritional factor limiting the growth of upland rice. Reliable indices of Fe deficiency are still lacking. Katyal (12) reported Fe deficiency symptoms in rice on calcareous soils with about 2 mg Fe^{2+}/litre in the soil solution. Foliar application of 0.1-0.5% aqueous solution of Fe sulfate or Fe citrate is recommended to correct Fe deficiency. The addition of quickly decomposing green manures, which decrease the pH, is an inexpensive and effective way to control Fe deficiency (27).

MANGANESE

Within the first weeks of submergence almost all active Mn in a soil is reduced to Mn^{2+} preceding the reduction of Fe. The reduction of Mn is both chemical and biochemical. Acid soils, high in Mn and organic matter, build up water-soluble Mn concentrations of more than 100 mg/litre immediately after submergence. The level declines thereafter to a stable concentration of around 10 mg/litre. In calcareous soils, the water-soluble Mn may not exceed even 0.5 mg/litre.

The concentration of soluble Mn^{2+} in the soil solution is highly dependent on both pH and redox potential. At pH levels below 5, the solubility is controlled by the pH alone (25). The effect of pH on the concentration of Mn^{2+} conforms to the equation

$$pH + 1/2 \log Mn^{2+} + 1/2 \log PCO_2 = 4.4$$

indicating an equilibrium with $MnCO_3$ (26).

Most wetland rice soils contain adequate levels of available Mn. Deficiency occurs on calcareous soils, sandy soils, and calcareous peat soils. Manganese toxicity could be one cause of poor performance of rice on acid upland soils (27). A deficiency level for Mn in flooded soils of <1 mg/kg (extracted in DTPA + $CaCl_2$ at pH 7.3) has been found useful (30). Manganese oxide is suggested as an amendment on flooded soils and

$MnSO_4$ on upland soils. Foliar application and soaking of seeds have been recommended, too. An alternative approach is the use of tolerant rice varieties.

SULFUR

In anaerobic soils, the main change related to S is the reduction of SO_4^{2-} to S^- by obligate anaerobic bacteria. In neutral to alkaline soils, concentrations of SO_4^{2-} as high as 1,500 ppm may be reduced to zero within some weeks of submergence. The equation (28)

$$Eh = 0.356 + 9.833 \times 10^{-3} - 0.079\ pH$$

or

$$pE = 6.04 - 1/6\ pSO_4 - 4/8\ pH$$

indicates that to lower the SO_4^{2-} concentration to 1 mg/litre a pE of -4.12 or Eh of -243 mV at pH 7 is needed. Since pE values of about -1 are common in wetland soils, S deficiency should occur only in highly reduced soils or in soils with low SO_4^{2-} content. But in microspots, and especially when CH_4 is produced, S deficiency is likely to occur. Reasonable tests for critical levels in wetland soils are still lacking. However, among the current methods, $Ca(H_2PO_4)_2$ as an extracting solution appears to be the most acceptable in separating S-deficient from nondeficient wetland rice soils. Critical S levels in wetland rice soils obtained by several investigators using $Ca(H_2PO_4)_2$ solution ranged from 7 to 11 mg/kg and averaged 9 mg/kg (38, 35, 39). Table 1 shows the S and SO_4^{2-} contents of wetland soils in some Asian countries. Since S deficiency is often combined with Zn deficiency, it is difficult to isolate the two.

On the basis of various reports, S-deficient soils in the humid region possess one or more of the following features: low organic matter content, high content of allophane or oxides, sandy texture, low content of total S, frequent burning of vegetation, and absence of pollutants.

Table 1. Total sulfur and sulfate sulfur content of wetland rice soil in four countries.

Country	Total S (ppm)		SO_4-S (ppm)		No. of soils	Reference
	Range	Mean	Range	Mean		
Philippines	76-817	407	2-150[a]	20	38	7, 19
Indonesia	20-149	97	1-16[b]	5	9	8
China	190-580	255	11-51[c]	22	152	17
Thailand[d]	–	–	1-428[a]	27	88	5

[a] $Ca(H_2PO_4)_2$ extractable available S. [b] Acetate extractable S. [c] 0.03 M NaH_2PO_4-2 N HOAc extractable S. [d] Most of the soils were planted to upland crops.

Sulfur shows one of the most complex cycles in nature because it exists in most oxidation states between -2 and +6 and forms a large variety of organic and inorganic species. Most S in soils occurs in organic (>95%) rather than in inorganic states (36). The organic forms of S in soil constitute different groups of compounds. Probably the most obvious one includes the S-containing amino acids and sulfonates (cysteine, methionine, taurine) in which S is directly bound to C in the reduced state of S^{2-}. These undergo dissimilation to H_2S, mercaptans, disulfides, NH_3, and fatty acids in anaerobic soils. Another group consists of organic esters of H_2SO_4, where S is bound to O in the form of $C\text{-}O\text{-}SO_3^-$ (esters of phenol, aliphatic alcohols, carbohydrates, and amino acids). The inorganic forms of S under anaerobic conditions are mainly S^- and even elemental S (2).

Because Fe reduction precedes SO_4^{2-} reduction, Fe^{2+} will always be present in the soil solution by the time H_2S is produced so that insoluble sulfides will be formed, causing the strong toxicity of H_2S (>0.07 mg/litre) to rice. Aside from Fe^{2+}, other ions -- Mn^{2+}, Cu^{2+}, and Zn^{2+} -- may be transferred to sulfides, too. Figure 2 shows the equilibrium distribution of S with Fe species. Only in soils low in active Fe, such as bleached sandy soils, peat soils, and some acid sulfate soils, may H_2S poison the plant.

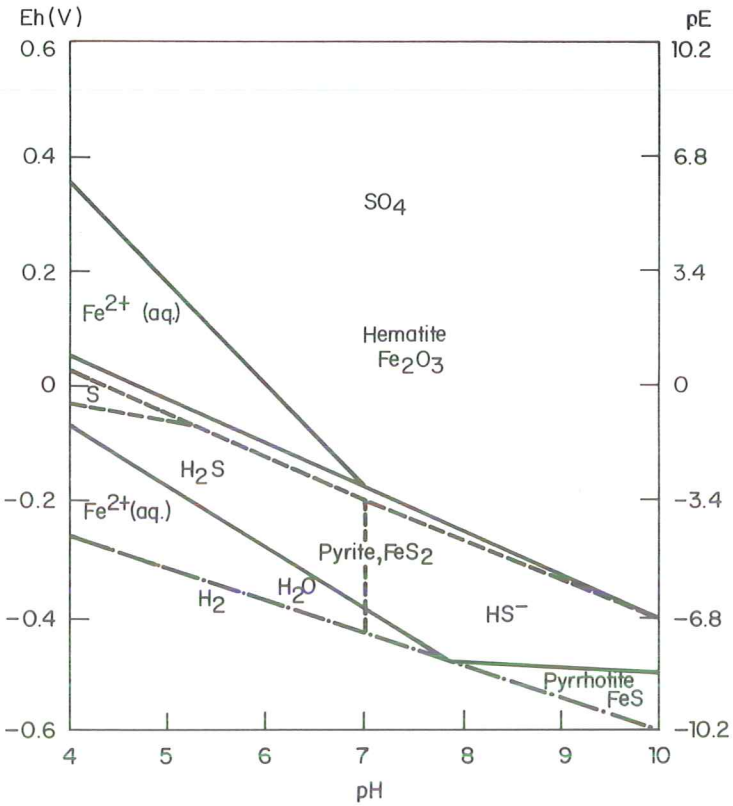
The most common sources of S are rain and irrigation water. Sulfur accretions from rain in the tropics and subtropics ranged from 1.0 to 32 kg/ha per year (4) depending on the distance from the seacoast, amount of rainfall, and proximity to industrial activities. Sulfur content in irrigation and river water varies greatly, ranging from 0.2 to 4.7 ppm (40). The world average is 4.1 ppm, while in Asia it is 2.8 ppm. Yoshida and Chaudhry (41) suggested that irrigation water with a S content of 2.7 ppm would be able to supply the entire needs of a rice crop.

As fertilizers, mostly $(NH_4)_2SO_4$ (24% S) and single superphosphate (14% S) are used. Blair et al (1) reported that gypsum and elemental S are as effective as $(NH_4)_2SO_4$ in wetland soils. The probable reason might be that sufficient oxidation of elemental S takes place in the root rhizosphere of rice.

ZINC

Zinc deficiency is the most widespread micronutritional disorder of food crops the world over. In wetland rice soils, after N, Zn is the most important nutrient limiting yields.

In mineral soils, Zn is found predominantly with the clay fraction (33). Zinc forms salts such as ZnS,



2. Equilibrium distribution of sulfur species in water at 25°C and 1 atm of total pressure. Activities of total dissolved sulfur and iron species are 10^{-3} and 10^{-4}, respectively. The equilibrium conditions for the sulfur system alone are indicated by the dashed lines (41).

sphalerite (ZnFe), zincite (ZnO), and smithsonite ($ZnCO_3$). These salts, except ZnS, are probably too soluble to persist in soil for a long time (15). In limited amounts, Zn is found on exchange sites of clay minerals and organic matter and is adsorbed on solid surfaces provided by amorphous oxides of Fe and Al (10) or by Ca and Mg carbonates or silicates (11). The intensity of adsorption increases as pH rises. It may be also possible that Zn^{2+} enters in the octohedral layer of clay minerals normally occupied by Al^{3+}.

Many authors have provided evidence for the complexation of Zn by humic fractions, which increases at higher pH values (13). More Zn is adsorbed in slightly basic than in acidic media, and the influence of pH is more pronounced in light-textured soils than in heavy clay-textured soils.

Zinc solubility decreases 100 times for each unit increase in pH (15), as seen from the following equation:

$$\text{soil Zn} + 2\ H^+ \rightleftharpoons Zn^{2+}$$

$$\log Zn^{2+} = 5.80 - 2\ pH$$

Submergence brings about a decline in Zn availability that is linked to pH changes and formation of insoluble Zn compounds. The solubility of different Zn compounds makes it unlikely that $Zn_3(PO_4)_2$, $ZnNH_4PO_4$, $ZnSiO_3$, $ZnCO_3$, and $Zn(OH)_2$ will be the solid phase controlling Zn concentration in the soil solution (15, 16, 22). The breakdown of Fe and Mn oxides upon flooding provides surfaces with a high adsorption capacity for Zn. Zinc may be strongly adsorbed on carbonates too, especially Mg carbonates (14). This confirms the fact that most Zn-deficient soils in the Philippines have a low or even inverted Ca-Mg ratio. Scharpenseel et al (32) found that, in wetland soils, highly significant negative correlations between available Zn and organic C content disappear when partial correlations are used, setting Mg and HCO_3 constant.

The reported Zn-fixing interaction with P fertilizer must still be elucidated. In rice fields, P application depressed Zn availability more with regard to native Zn in the soil than to newly applied Zn (20). Most probably organic metal-phosphate complexes are formed.

On marginally Zn-deficient soils, it has been observed that rice varieties tolerant of Zn deficiency gave no or negative response to Zn application. Varietal tolerance for Zn deficiency was found to be related to lower Zn requirements and the ability to maintain lower Fe-Zn, Cu-Zn, Mg-Zn, and P-Zn ratios in the shoot. Zinc is involved in the root-to-shoot translocation mechanisms of these elements. Adding Zn to a marginally Zn-deficient soil further reduces these nutrient ratios, creating induced deficiencies and mineral imbalances in the resistant varieties (7). Alkaline floodwater aggregates these imbalances. Organic amendments could cause or aggravate Zn deficiency, most probably because of enhanced pH-Eh changes and increased HCO_3^- formation (7). Singhania et al (34) reported that availability in plants of Zn from aerobically decomposed cow dung + straw enriched with Zn was less and that from anaerobically decomposed cow dung slurry was more than that of equal amounts of $ZnSO_4$.

The rate of Zn application to soil depends upon soil characteristics, source of Zn, severity of deficiency, and rice variety to be grown. Application of 10 kg Zn/ha or root dipping in 2% ZnO is adequate in most situations. Application into the floodwater or to the soil surface was found more efficient than incorporation (21).

COPPER

Copper is present in soils as oxides, carbonates, silicates, and sulfides. The chemistry of Cu in submerged soils is similar to that of Zn, forming sparingly soluble sulfides. The precipitation of Cu as hydroxide, carbonate, or phosphate is unlikely below pH 7. Ponnamperuma et al (29) found evidence of this and proposed a tentative soil critical limit of 0.1 mg/kg for Cu deficiency extractable by 0.05 HCl. Copper is reported to be the most deficient micronutrient of crops in ombrogenous peat soils (3). In peat soils of the Philippines, mostly topogeneous peats, Cu response is small, while Zn response is substantial, probably because of sufficient influx of Cu from adjacent terrain.

While Cu complexation with organic ligands increases at pH 5.0, it precedes Zn, which becomes more complex only above pH 6.5 (31). Therefore, precipitation or adsorption is more limited for Cu, and its availability is less pH dependent. Above pH 7, almost all Cu^{2+} and Zn^{2+} ions are chelated in the soil solution. The stronger complexation of Cu and higher stability of these complexes in the soil solution may be the reason why Cu deficiency is not as prevalent as Zn deficiency in submerged soils and at high pH levels.

Copper deficiency may be controlled by soil and spray application of Cu_2O or $CuSO_4$. A rate of 3-6 kg Cu/ha at 3-year intervals is sufficient in most cases. If blue-green algae are desired for N fixation, the concentration of Cu in the floodwater should be carefully controlled, because algae are sensitive to Cu.

MOLYBDENUM

Molybdenum plays an important role in metabolism, reducing NO_3^- to NH_4^+. It is present in soils mostly as a substitute for Fe and Al in silicates. Clayey soils have a higher Mo content than sandy soils, and soils developed on acidic parent rocks have higher contents than soils from basic rocks.

Molybdenum is released predominantly as the MoO_4^{2-} anion above pH 5.6, while $HMoO_4^-$ is formed at lower pH. The solubility of Mo is given by the equation (15)

$$\text{soil Mo} + 2H^+ \rightleftharpoons MoO_4^{2-}$$

$$MoO_4^{2-} = 10^{-20.5}\ (H^+)^2$$

The MoO_4^{2-} concentration increases 100-fold for each unit increase in pH. The critical level for deficiency is assumed to be 0.15 mg/litre in soil solution.

Molybdenum has a strong affinity for Fe and is adsorbed mainly on sesquioxides in addition to organic matter and clay minerals. Therefore, hydromorphic soils and peaty soils are often rich in total Mo content.

Since the availability of Mo is correlated positively with pH and negatively with active Fe oxide content, Mo deficiency in wetland rice soils seldom occurs. Molybdenum deficiency in wetland rice has been reported by Tang (37), who found that in China the supply of Mo to rice plants is usually insufficient in acid and neutral wetland soils, while in calcareous ones it is determined mainly by the nature of the parent material.

Low or zero response to Mo application in wetland rice might be related to the fact that wetland rice takes up NH_4^+ instead of NO_3^-.

BORON

Boron deficiency is common worldwide on acid and alkaline upland soils, especially when combined with drought. Boron deficiency (<0.5 mg/kg) in rice has been reported in China, chiefly in acid soils (18). But B toxicity may be more common in wetland rice soils than currently recognized. Boron toxicity (>5 mg/kg) is likely to occur in rice on sodic and saline soils and soils irrigated with water containing >2 mg B/litre. This value is often exceeded by deep well water in volcanic and hydrothermal areas in the Philippines.

Boron exists in the soil mainly as H_3BO_3, a weak acid, or as readily soluble salts. Below pH 6 it is almost undissociated. With increasing pH the dissociation is enhanced and $B(OH)_4^-$ ions are formed. The concentration in the soil solution is often below 0.1 mg B/litre because of strong adsorption by organic matter as well as sesquioxides and clay minerals, especially illites and vermiculites (31). The soil C content is often positively correlated with hot water extractable B. Boron adsorption increases with increasing pH. Possibly, the $B(OH)_4^-$ ions are bound due to alcoholic groups of organic substances of OH groups of sesquioxides. Submergence increases B availability. Because of the higher temperature of the soil solution in the tropics (up to 35°C in the topsoil) the release of B into the soil solution is increased. Consequently, irrigation water with high B concentration and high temperature should be cooled down before running into the field. On the other hand, excess B contents are easily leached out in tropical wetland soils if irrigation water with low B concentration is available (7).

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SOIL FERTILITY AND FERTILIZER MANAGEMENT OF RICE-BASED CROPPING SEQUENCES

R. A. MORRIS and O. P. MEELU

The rice lands of tropical and subtropical Asia support a large and growing population. Cropping intensification, which must occur on these rice lands, will require applications of mineral nutrients to keep crop yields high. In this resource-poor region, it will be important to increase the efficiency of inorganic fertilizers, to seek substitutes for costly inorganic fertilizers, and to integrate the use of inorganic and organic nutrient sources. Short- and long-term residual effects are discussed for the major crop nutrients. In lowland rice-based cropping sequences, the soil passes through an annual anaerobic-aerobic cycle. Implications of nutrient transformations and consequent changes in nutrient availability associated with soil oxidation states influence the efficiency of inorganic and organic nutrient applications. In a sequence of lowland rice and dryland crops, the crop in the sequence that receives a nutrient influences the efficiency of the nutrient in the sequence. Research suggests that inorganic and organic amendments can be integrated to produce high and economic yields from multiple cropped sequences without adversely affecting soil productivity.

A large proportion of the world's population is concentrated in the major lowland rice-growing regions of Asia. To meet the accelerating needs of this population, production intensification through the adoption of modern agricultural technology and multiple cropping is being advocated. Intensification, however, increases crop demand for nutrients; native soil fertility is not sufficient to increase yields, and therefore recourse has to be made to the application of amendments. To maintain production at high levels, it is important not only to increase fertilizer-use

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efficiency but also to seek substitutes for costly chemical fertilizers. The judicious and complementary use of inorganic and organic amendments must be considered in resource-poor situations.

In lowland rice cultivation, as practiced in Asia, the soil is commonly submerged for most of the crop growth cycle. To a significant degree the field water regime (the annual field water status relative to optimal levels for different crops during the year) determines the cropping potential. The field water regime determines the seasonal pattern of water availability, the suitability for field operations, soil aeration, and, to an important degree, the nutrient availability. The annual rainfall pattern plus terrain and soil characteristics determine the field water regime. Thus, except where irrigation and drainage control are intensive and reliable throughout the year, the cropping potential largely depends on the rainfall pattern, with terrain and soil features creating local variations.

In this paper, we address several questions relevant to the management of cropping sequences that include a puddled lowland rice crop. We do not address the risk problem, one that is especially real under rainfed farming conditions.

The peculiar nature of soil management for rice, and its influence on soil physical properties and the temporal variation in nutrient-supplying power it causes, is an important consideration that must influence nutrient management strategies for rice-based cropping sequences. Thus, the "rice-based" aspect of our subject has some relevance because of

- the effect of soil puddling and submergence on nutrient transformations,
- the residual physical properties of the soil, and
- the soil profile that commonly develops following a comparatively few years of lowland rice cultivation.

Other papers in this workshop describe the characteristics of soils on which rice is grown, the nutrient-supplying power of soils, and the physical and chemical changes that occur during land preparation for rice. Although these are important matters, we concentrate here on the management of amendments to meet crop nutrient needs. Movement of nutrients from the soil solid phase (mineral and organic) to the adsorbed and solution phases depends on both environment and management variables. We are primarily interested in management variables because through them a farmer can influence nutrient availability. Environment determines the constraints within which management decisions may be made. Soil mineral and organic components are comparatively fixed in the short run. Soil water and

air content, however, can be altered by management practices. The nature and concentrations of amendments and the time they are applied are controlled by management practices. The greater the time lapse between the application of an amendment and its removal by a crop, the greater is the chance that a potential phase change will become a real change. Some changes are undesirable (P fixation) and others desirable (N mineralization).

Most farmers operating rice-based cropping sequences in tropical Asia are constrained by lack of capital and seldom apply fertilizers at levels where the cost of the last kilogram of nutrient equals the value of output derived from it. The efficiency of the quantities that these farmers apply may be improved by changing the time of application or the placement, or both -- changes that are within the management scope of farmers.

INORGANIC NITROGEN

Soils are generally deficient in N, and cereals invariably respond significantly to its application. For example, Table 1 shows that in three Indian states, rice and wheat responded to N applications as high as 120 kg N/ha, but yields without N and N response rates differed.

The efficiency of different N fertilizers is determined by the form of N, the crop to be grown, and the agroecosystem. The results of many studies on rice have revealed that NO_3^- sources of N are inferior to NH_2 and NH_4^+ forms (17, 28). In the case of wheat, however, the three sources have been reported generally equally effective (31). Recently Meelu et al (21) compared urea and calcium ammonium nitrate sources in a rice-wheat rotation and obtained similar results. Their study showed that rice was sensitive to N source and time of application but wheat was not (Table 2).

If the crop's pattern of N uptake and the soil's ability to supply N are considered, N fertilizer applications can be timed to coincide with the period

Table 1. Response of rice and wheat to nitrogen applications in 3 Indian states (10).

Location	Crop	Yield w/o N (t/ha)	Response to N (t/ha)			C. D. (5%)
			N40	N80	N120	
Kalayani (W. B.)	Rice	1.41	0.84	1.70	2.3	0.15
Kalayani (W. B.)	Wheat	1.24	1.44	2.52	3.48	0.51
Pura (U. P.)	Rice	3.22	0.52	0.97	1.25	0.14
Varanai (U. P.)	Wheat	1.27	1.22	2.17	2.73	0.14
Jabalpur (M. P.)	Rice	1.34	1.61	2.04	2.53	0.12
Sehore (M. P.)	Wheat	2.46	1.09	1.52	1.98	0.26

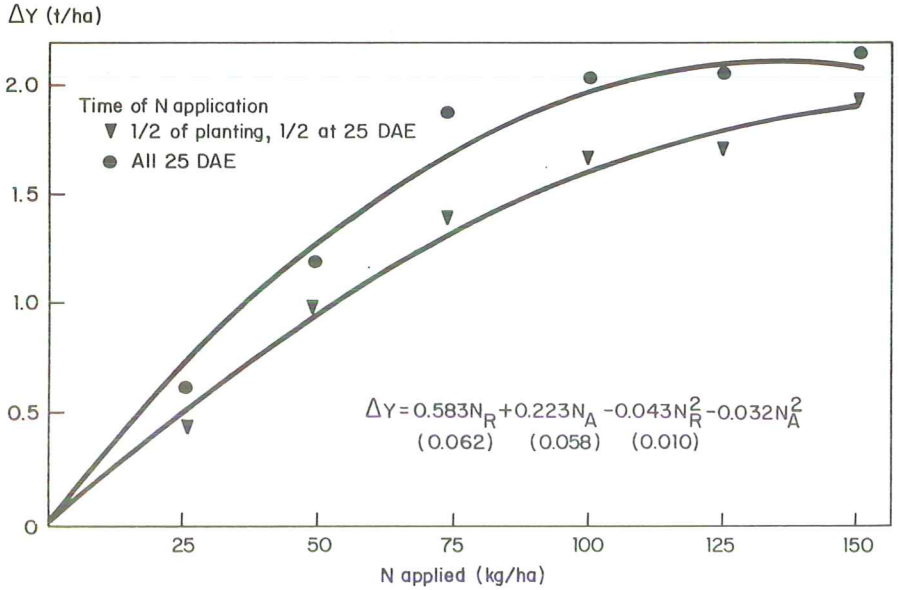
Table 2. Effects of split applications of nitrogen on rice and wheat yields, 1975-1977.

N split	Grain yield (t/ha)	
	Rice	Wheat
0 - 1 - 0	4.73	4.32
1/2 - 1/2 - 0	5.24	4.38
1/2 - 0 - 1/2	5.36	4.35
0 - 1/2 - 1/2	5.17	4.52
1/3 - 1/3 - 1/3	5.58	4.33
C. D. (5%)	0.21	N. S.

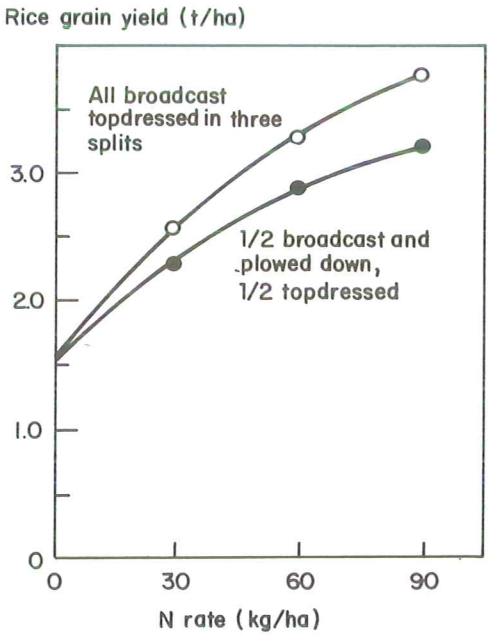
in which the difference between expected soil N supply and crop uptake rate is greatest. Provided that N can be effectively extracted by roots, a delayed timing will lessen the chance of its being immobilized or lost. N applied at low and intermediate rates just before a strong demand by a crop should augment soil N most effectively. Because NO_3^- accumulates in the soil of a fallow field, available soil N will often be enough to satisfy early crop requirements, especially if N demand during the peak uptake period cannot be met by soil or fertilizer N. Experiments testing intermediate N levels have tended to support the view that soil N is adequate for early crop needs. For example, an experiment on irrigated maize showed that at intermediate N rates all N topdressed 25 days after emergence (DAE) was more efficient than split-applied N (Fig. 1). As the N rate increased, the relative efficiency of the single application diminished. In two experiments in which intermediate N rates were applied to rice drilled directly on unpuddled soils, N fertilizer increased when the broadcast-incorporation at planting was eliminated (Fig. 2, 3). In those experiments, N uptake rates averaged 0.4 kg/day between 10 and 30 DAE. The uptake rate increased to 1.4 kg N/day between 30 DAE and panicle initiation.

Studies with ^{15}N have shown that only 3-4% of the N applied to a rice crop is normally recovered by a subsequent rice or wheat crop (13, 29). In the Philippines, the residual response to 180 kg N/ha, a rate at which N efficiency in the first crop was low, was less than 150 kg/ha even when the second crop was transplanted only 9 days after harvest of the first (12).

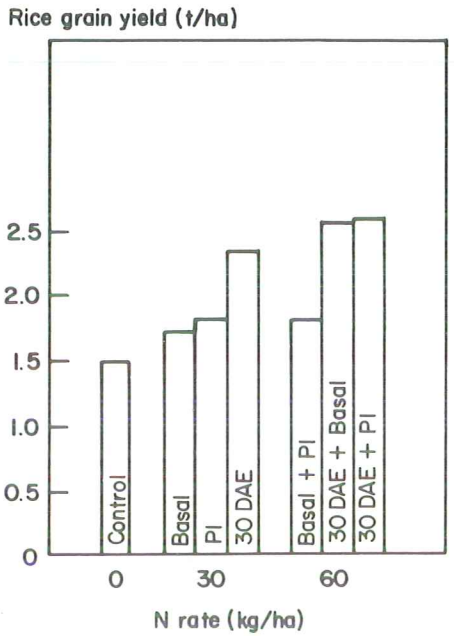
Where N applications to a crop preceding rice are likely to be excessive, as with vegetables, substantial residual effects on rice can be expected (9). Nitrogen uptakes from fallowed soil and from soil to which low and high N levels were applied on vegetables are compared in Figure 4. Nitrogen derived from the residues of vegetables that had received heavy N applications



1. Maize yield responses to single (all at 25 DAE) and split (1/2 at planting, 1/2 at 25 DAE) applied N fertilizer. IRRI, 1983 dry season.



2. Response of direct-seeded rice to N fertilizer rates that were split 3 times without a basal application or 2 times with a basal application. IRRI, 1979 wet season (25).

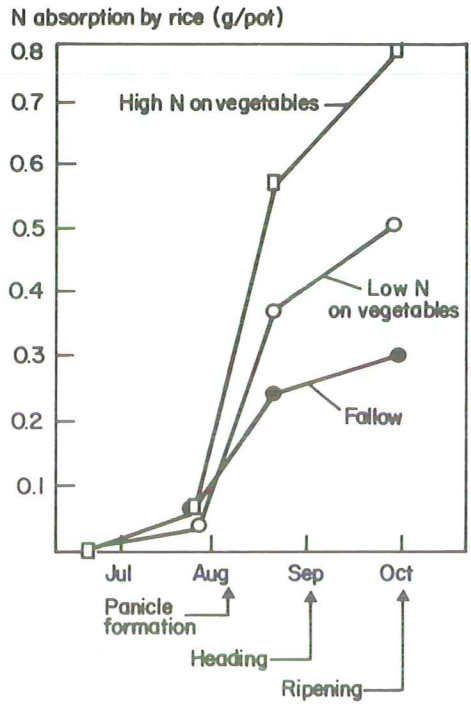


3. Response of direct-seeded rice to 30 kg N/ha applied at planting (basal), at 30 DAE, and at panicle initiation (PI), singly and in pairwise combinations. IRRI, 1979 wet season (34).

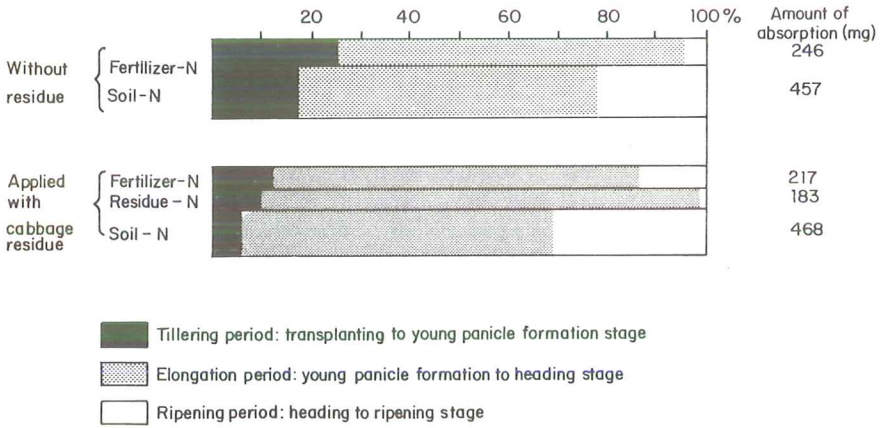
was recovered more efficiently and earlier than N from $(NH_4)_2SO_4$ (Fig. 5).

A short-maturity cash catch crop or green manure crop can effectively use the NO_3^- that becomes available during the period before land is prepared for rice. Many studies have shown that, by growing a grain legume or forage crop before a cereal, the N production function is shifted to the left. For example, Figure 6 shows that maize following mungbean yielded higher than maize following cereals only where inorganic N had not been applied.

Recovery of inorganic N applied to rice or to upland crops seldom exceeds 50%. Although much N is lost from the soil by denitrification, leaching, and volatilization, a variable portion is incorporated into the soil organic fraction. Soil N may increase after many years of frequent inorganic N applications (15). Mineralization of this increased soil N effectively increases the N available to the crop. (A net positive N balance may not always be achieved, as will be discussed later.) Assuming the N mineralization rate to be 5% per crop (13), many years of accumulation are needed before the influence of accumulated N is clearly observed as a yield increase. For example, if a net 15 kg N/ha is immobilized per year, 5 is mineralized per

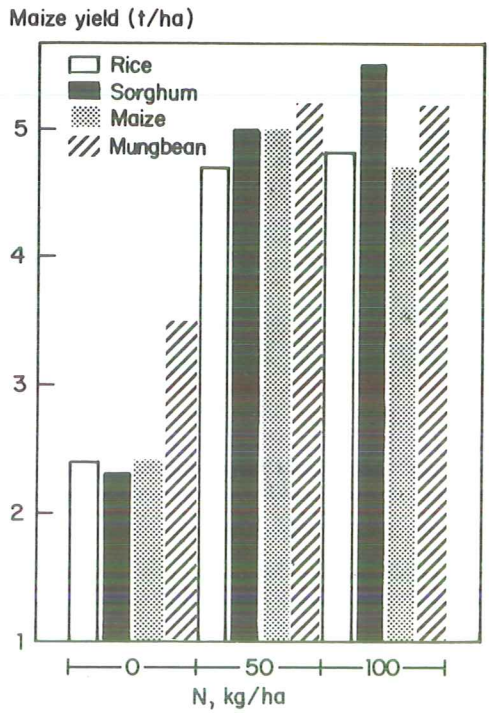


4. Adsorption of soil N by rice plants at different growth stages (9).



5. Growth periods and percentage of N absorption by rice, where total absorption equals 100 (9).

crop, and response is about 70 kg grain yield/kg N uptake (40), 8 years will elapse before a yield response of 400 kg grain/ha is detected statistically at common levels of experimental precision.



6. The effect of four preceding crops (upland rice, soybean, maize, and mungbean) on the yield of maize at 0, 50, and 100 kg N/ha. IRRI, 1983.

INORGANIC PHOSPHORUS

Katyal (14) and Fried and Broeshart (4) reported that, for rice, surface applications of P were more efficient than incorporation. Katyal found that P fertilizer efficiency declined if application was delayed more than 7 days after transplanting. Depending on the nature of the root system, the P fertilizer, and its reaction with the soil, P fertilizer management principles for major upland crops are well recognized; but, in practice, management is subject to the limits of placement options open to farmers.

Most P-response data pertain to the crop to which P was directly applied. However, only 15-20% of the applied P fertilizer is generally utilized by a crop; the rest is retained in the soil. In actual practice, however, crops are grown in frequently repeated sequences, and residual effects can be important, especially if crop P requirements differ. This is substantiated by long-term experiments in rice-based cropping sequences (Table 3). The data show that when 26.25 kg P/ha was applied to wheat or dry season (rabi) rice, application of P to wet season (kharif) rice could be omitted with little reduction in yield.

Table 3. Total responses (t/ha) to applications in rice-based cropping sequences.

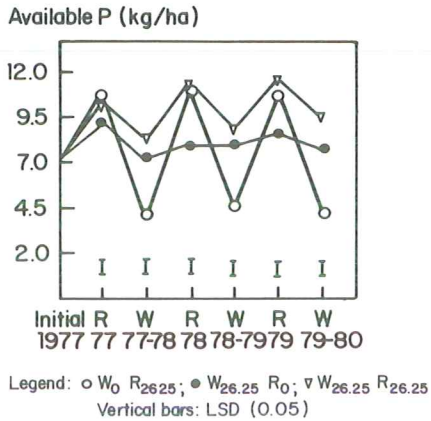
Crop rotation, location, soil	Response (t/ha) to 26.25 kg P/ha applied			
	To both crops	In *kharif* only	In *rabi* only	Reference
Rice-wheat				
Ludhiana (Punjab) Alluvial	6.54	4.68	6.47	6
Masoda (U. P.) Alluvial	1.90	1.19	1.73	8
Rice-rice				
Nandyal (A. P.) Med. black	1.83	2.09	2.59	10
Chiplima (Orissa) Red and yellow	0.74	0.74	0.89	10
Maruteru (A. P.) Med. black	0.22	0.31	0.63	10

Critical soil test levels are usually higher for upland crops than for rice. Research in the Philippines established the critical Olsen P level for rice at 10 ppm and for other field crops at 20 ppm (24). Dhillon et al (3) reported that on Punjab soils, critical Bray P_1 levels were 8 ppm for wheat and 6 ppm for rice. Hayami (9) found that for tomato the critical level for available soil P was higher than that for rice by a factor of 3 or more and therefore P applied to meet the requirement of tomato would leave sufficient P for rice. Hayami tested 14 paddy soils and found that A-values for rice averaged 60% higher than those for vegetables.

The different critical P levels for rice and upland crops may be attributed to several factors, but release of P from $Fe\text{-}PO_4$ compounds upon soil reduction is perhaps of major importance (26). After rice harvest, reoxidation diminishes P availability. Mechanisms responsible for diminished availability are discussed by Willet et al (42) and Willet and Higgins (41).

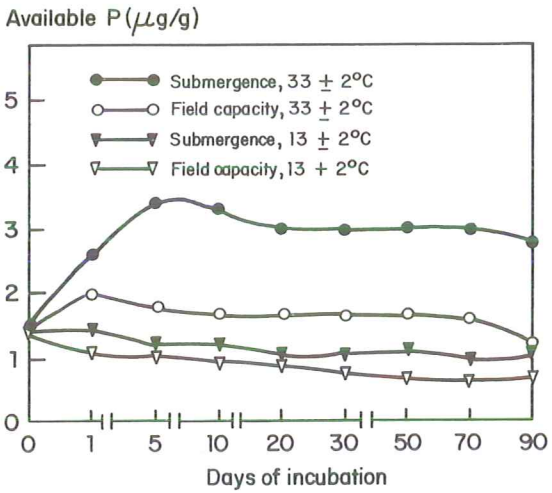
Studies by Gill and Meelu (6) showed that the availability of P, where P was applied only to rice in a rice-wheat rotation, declined during the wheat cropping period (Fig. 7). Figure 8 suggests that two factors -- submergence during the rice cropping period and cool temperatures during the wheat cropping period -- contributed to changes in P availability in the rice-wheat sequence.

There are apparent exceptions to the general rule of rice having a lower critical level than nonrice crops grown on the same soil. From long-term fertility studies on reclaimed sodic soils, Chhabra and Abrol (2) reported no response by wheat to P applied directly to

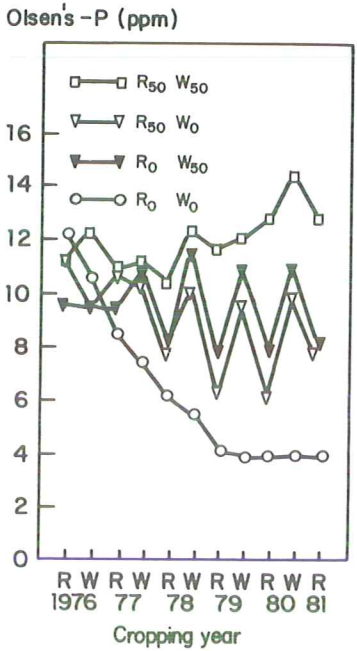


7. Changes in available P after harvesting rice (R) and wheat (W) in rice-wheat cropping sequence (6).

the wheat or to the preceding rice crop. They found, however, that P applications to the rice crop and to the preceding wheat crop increased rice yields, but there was some evidence of higher efficiency where P was applied directly to the rice. Following regular P applications that apparently exceeded crop removals, Chhabra and Abrol reported available soil P accumulations in a long-term rice-wheat sequence (Fig. 9). Where P was not applied, available P declined rapidly during the first seven croppings. The P-response pattern observed in the study by Chhabra and Abrol may have resulted from a much higher P demand by rice than



8. Effect of incubation temperature and soil moisture regime on changes in available P of soil (6).



9. Changes in Olsen extractable P from 0-15 cm soil depth as affected by P application to a rice-wheat crop rotation. R_0,W_0 = without P to either rice or wheat; R_{50} = 22 kg P/ha applied to rice (R) and wheat (W), respectively (2).

by the wheat with which it was rotated. Rice and wheat yields from the highest P regime averaged 8.8 and 4.6 t/ha during the last year (1980-81), as reported by Chhabra and Abrol.

INORGANIC POTASSIUM

Yield responses to inorganic K applied to either rice or upland crops in rice-based cropping sequences are much less common than responses to N or P. Data available to support general statements regarding K management are inadequate, but, on the basis of general principles, K applications should be given preferentially to nonrice crops in the system, especially if these crops have high K requirements as do maize and tomato. The total K uptake by root crops and coarse grains (maize and sorghum) is greater than that of rice, small grains, and grain legumes (37). Furthermore, flooding increases K concentration in the soil solution. Under reduced conditions, Fe^{2+} and NH_4^+ are released by various processes and displace K^+

from exchange sites, increasing the K concentration in solution and, therefore, its availability to rice (23). However, because the roots of lowland rice do not penetrate as deeply as those of upland field crops, rice will not benefit greatly from soil mineral K sources below 25 cm. If K has been depleted from the surface soil but subsurface levels are high, it may be more beneficially applied to rice, with upland crops using residual and subsurface soil sources. The significance of K below the plow layer is suggested by data from Ganeshamurthy (5), who reported that up to 80% of the soil K removed by sequences of maize-wheat and maize-wheat-cowpea came from below the plow layer. The amounts of K removed were greatest when fertilizers (including K) had been applied to remove N, P, and K nutrient deficiencies.

The contribution of K from decomposed or burned rice straw is substantial (27). Provided that residues from crops that retain high K levels in vegetative organs are returned to the soil, inorganic K inputs to meet crop requirements should be low.

ORGANIC AMENDMENTS

Four organic amendment classes are recognized: farmyard manure (FYM), compost, straw, and green manure (GM). None are standardized with respect to nutrient concentrations or availability factors. All are bulky, comparatively difficult to incorporate, and costly to transport.

Farmyard manure and compost

Approximate nutrient compositions of crop residues (straw), animal wastes, compost, and GM are given in Table 4. The variation in compost and FYM is evident from Table 5. If applied liberally and frequently, all organic amendments tend to increase the soil organic fraction and increase the availability of N, P, and K, especially if inorganic materials are added with the organic amendments and if the organic amendments originated from sources other than the field to which they are being returned. Composts and other high C N materials should benefit soils that are coarse textured and low in organic matter, CEC, and weatherable minerals. Their regular and liberal applications should increase the nutrient contents and CEC of such soils. The exceptions are associated mostly with intensified cropping, where the accumulation of small negative nutrient balances per crop may become evident within a few seasons.

Koyama and App (15) presented a N balance covering a 21-year period for a 3-year rice-rice-rye rotation grown on a well-drained loam in Japan. Without

Table 4. Approximate composition of various organic substances (35).

Substance	Composition (%)			
	N	P	K	C:N
Crop residue (straw)	0.5	0.09	1.3	65
Animal feces	3	0.65	0.8	15
Animal urine	20	0.04	16.6	2
Compost	1.5	0.17	0.8	15
Green manure	3	0.26	2.1	11

application of FYM or inorganic N, soil N declined by 36%. Where FYM (totalling 2,045 kg N/ha over the 21 years) was applied, soil N also declined, but by only 21%. A total inorganic N application of 4,190 kg/ha, in addition to 2,045 kg N/ha from FYM, was necessary to maintain soil N at its original content. By comparison, on a heavier soil at a different location, where continuous rice cropping was practiced, an application of only 1,202 kg N/ha from FYM was required to maintain soil N at its original content. FYM applications containing 2,003 kg N/ha increased soil N content by 39%.

From Korean experiences, Oh (22) suggested that FYM and composts are more favorably applied to dryland crops than to irrigated rice. He maintained that irrigated rice soils are enriched by natural nutrient supplies. Meelu (18), however, presented data showing that applying FYM to wet season rice will be more effective (in terms of total grain output) than applying it to dry season wheat. The residual effect on wheat of FYM applied to the preceding rice crop was much greater than the residual effect on rice of FYM applied to wheat. The residual effect on wheat was 0.8 t/ha in the last 2 years reported (7). The FYM in this

Table 5. Chemical composition of 105 samples of compost and farmyard manure from 4 sites in Ibaraki-ken, Japan (11).

Component	Composition (%)		
	Mean value	Highest value	Lowest value
H_2O	75 ± 12	93	40
pH (H_2O)	7.9 ± 0.8	9.4	5.9
C	7.9 ± 2.1	13.3	1.4
N	0.39 ± 0.17	1.07	0.07
C:N	20.3 ± 6.5	46.0	4.7
P	0.08 ± 0.04	0.24	0.01
K	0.58 ± 0.37	1.84	0.07
Ca	0.32 ± 0.16	1.06	0.06
Mg	0.08 ± 0.04	0.29	0.01
Si	2.1 ± 0.7	7.7	0.01

study was carbonaceous and low in N (0.63% N, C:N=24.6). For this amendment, mineralization would likely have proceeded more effectively under aerobic conditions (43).

Straw

Where draft capacity is restricted, straw is often regarded as a nuisance because it makes plowing difficult. Hauling, composting, and respreading are laborious tasks that are economical only where wages are low. On many farms, therefore, straw and the organic C and N potential in straw are foregone.

According to Ponnamperuma (27), 1 t rice straw contains 6 kg N, 1 kg P, and 15 kg K/ha. Four tons of rice straw from 3-t/ha rice grain crop, if incorporated, would return 24 kg N, 4 kg P, and 60 kg K/ha. Moreover, because straw incorporation stimulates nonsymbiotic N fixation in flooded soils, additional N will become available to the rice crop. Rice yield increases of about 0.2-0.3 t/ha have been demonstrated after straw incorporation. Williams et al (43) concluded, however, that the N percentage threshold for N mineralization was 0.54. Yield responses were more sensitive to straw N percentage than to quantity of straw.

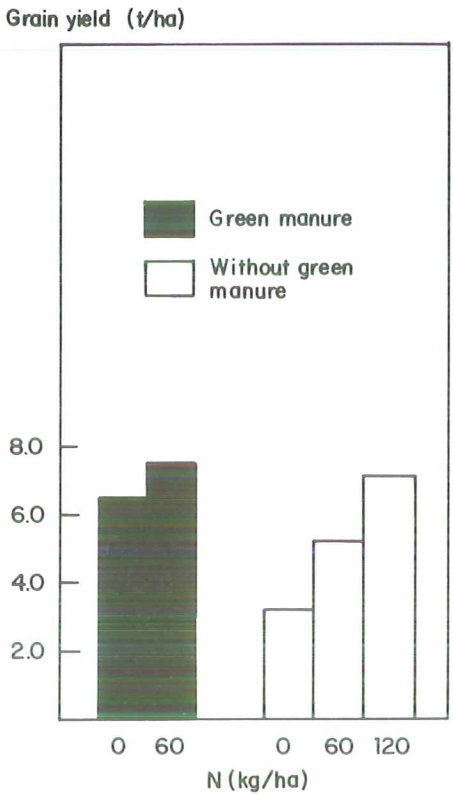
In an experiment repeated 3 years on a Punjab soil, Meelu and Rekhi (20) reported substantial rice yield increases from mungbean straw incorporation into a low N status soil (Fig. 10).

In Taiwan, the incorporation of rice straw and soybean stover in a rice-rice-soybean sequence had a negligible effect on rice yields, but returning residues increased soybean yields (Table 6). Crop residue incorporation, however, increased several soil fertility parameters.

Green manures

The N contribution from green manuring is well appreciated. As a general rule, green manuring, to be viable, should not compete with economic food or cash crops. One possibility is to grow a GM crop during short periods of fallow either before or after rice (see Fig. 11). Significant effects on yield were obtained by incorporating GM at 30 DAE. Williams et al (44) reported over 100% apparent recovery from low levels of GM (containing 33 kg N/ha) incorporated before rice. Recovery diminished to 50% following high levels of GM incorporation (containing 120 kg N/ha).

Su (33) reported comparisons of the effects of organic manures, GM, and inorganic fertilizer on rice yields in China (Table 7). On an equal-N basis, GM was as effective as inorganic N. N in soybean cake and fish scraps was more effective than inorganic N, and compost was less effective.

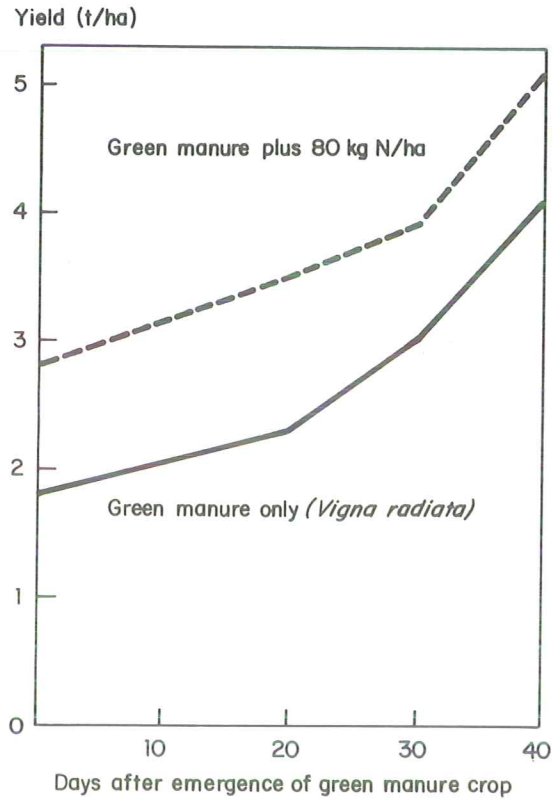


10. Effect of summer mung straw (green manure) on rice yield, 1980-82 (20).

Table 6. Mean yields of rice and soybean in a long-term trial on application of crop residues in old alluvial soil at Wanluan, means of 7 years, 1974-1981 (R. S. Lo, Kaohsiung District Agricultural Improvement Station).

Item	− Residue	+ Residue
Crop yield (t/ha)		
1st rice	6.84	6.85
2nd rice	4.73	4.77
Soybean	2.00	2.25
Soil analysis		
pH	5.5	5.5
Organic matter (%)	2.9	3.1
Available P (ppm)	38	41
Available K (ppm)	65	87

While there are no comparative data showing that GM is more efficient when incorporated before a rice or a nonrice crop, the difference between anaerobic and aerobic mineralization indicates that incorporation before the rice crop should be preferred.



11. Rice yields from mungbean incorporated as 20, 30, and 80 day old green manure crops, with and without 80 kg N fertilizer/ha, applied to rice, means of 3 years. IRRI, wet season.

Table 7. Paddy yield efficiencies at 2 nitrogen levels (80 and 120 kg/ha) of organic fertilizer and $(NH_4)_2SO_4$, mean of 52 trials.

Source of N	Paddy yield increment (kg grain/kg N applied)					
	1st crop			2nd crop		
	80	120	Mean	80	120	Mean
Soybean	14.5	10.5	12.5	9.8	8.8	9.3
Fish scraps	12.3	9.5	10.9	10.3	8.1	9.2
Green manure	10.3	8.9	9.9	7.6	6.3	7.0
Compost	6.6	6.4	6.5	5.8	5.1	5.5
$(NH_4)_2SO_4$	10.6	7.8	9.2	7.3	7.4	7.4

INTEGRATED USE OF ORGANIC MANURES AND INORGANIC FERTILIZERS

The beneficial effects of FYM, compost, straw, and GM have long been known. Under intensive cropping, however, supplemental inorganic nutrients are often needed to achieve crop yield potentials.

Sahu and Nayak (30) studied the effects of inorganic fertilizers, alone and in combination with FYM and GM, on low N-responsive traditional rices (Table 8). The data show that applications of FYM and GM gave higher yields than an application of 22.5 kg N/ha. Tiwari et al studied the effect of green manuring in a rice-wheat sequence (Table 9). Rice that received GM gave a yield response equal to about 40 kg N/ha, and the succeeding wheat crop showed a residual effect.

Beri and Meelu (1) reported 3 years of results on green manuring with Sesbania aculeata in a rice-wheat sequence (Fig. 12). They obtained a N substitution equivalent to 60 kg/ha in rice but, like Singh (32), observed no residual effect on wheat.

Williams et al (44) demonstrated that an autumn-planted vetch grown during the winter and incorporated as GM produced an average rice yield response equivalent to 45 kg N/ha over 5 years (Table 10). An additional 90 kg inorganic N/ha was necessary to obtain a yield equivalent to that obtained from 135 kg inorganic N/ha.

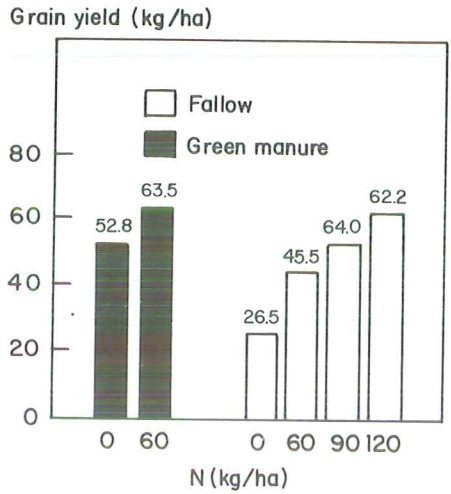
Table 8. Effects of organic manure with or without $(NH_4)_2SO_4$ on yields of traditional rice, 1956-65.

Treatment (kg N/ha)	Yield (t/ha)		
	Fallow	FYM[a]	GM[b]
0	2.15	2.44	2.55
22.5	2.35	2.47	2.41
45.0	2.36	2.67	2.50

[a]Farmyard manure. [b]Green manure.

Table 9. Nitrogen economy in a rice-wheat sequence supplied with green manure and inorganic nitrogen (38).

N (kg/ha)	Rice grain yield (t/ha)		Residual effect on wheat (t/ha)	
	Fallow	Green manure	Fallow	Green manure
0	2.37	3.85	1.67	2.37
40	4.04	4.91	1.71	2.78
80	4.63	5.27	1.88	3.18
120	4.98	5.37	2.27	3.35
C. D. (5%)				
N levels	0.5		0.12	
Green manure	0.36		0.09	



12. Effect of green manuring on nitrogen economy in rice (1).

Table 10. Effect of straw management and nitrogen fertility treatment on grain and straw yield and nitrogen economy of rice, mean of 5 crops (44).

Straw and vetch treatment	Grain yield (t/ha)			
	0 N	45 N	90 N	135 N
Returned	3.0	4.5	5.9	6.3
Burned	3.0	4.7	5.8	6.4
Returned + vetch	4.7	5.8	6.2	6.1
Burned + vetch	5.0	5.6	6.4	6.1

Kulkarni et al (16) combined organic and inorganic amendments in a rice-wheat sequence (Table 11). On alluvial soils, the combined use of 12 t FYM/ha and 60 kg N/ha gave as much rice yield as did 120 kg N/ha, indicating a substitution for 60 kg N/ha. But on red and yellow soils, a savings of 60 kg N, 26 kg P, and 50 kg K was obtained. FYM also produced residual effects on the succeeding wheat crop.

Teppoolpon and Wasinarat (36) reported the results of a study on the complementary use of compost and inorganic fertilizers on rice in Thailand (Table 12). The data indicate that the application of 2-6 t compost/ha increased rice yield, in effect saving 25 kg N/ha. Meelu et al (19) showed that 12 t FYM/ha increased mean rice yields by 0.7 t/ha, but 80 kg/ha supplemental inorganic N increased yields by an additional 2.9 t/ha (Table 13). Residual effects of FYM on the following wheat crop averaged 0.8 t/ha. Furthermore, Gill and Meelu (7) reported a buildup of soil fertility with FYM application (Table 14).

Table 11. Effect of combined use of organic and inorganic fertilizers in rice-wheat sequence on cultivators fields, 1974-75 to 1976-77.

Crop	Treatment[a]	Grain yield (t/ha)	
		Bhagalpur, alluvial soils (means of 87 trials)	Manipur, red and yellow soils (means of 46 trials)
Rice	F_0N_0	2.18	3.33
Wheat	F_0N_0	1.57	0.57
Rice	F_0N_{120}	4.21	4.41
Wheat	F_0N_{60}	2.75	1.04
Rice	$F_0N_{120}P_{26}K_{50}$	4.97	5.39
Wheat	F_0N_{60}	3.02	1.36
Rice	$F_{12}N_{60}$	4.14	5.44
Wheat	F_0N_{60}	2.95	1.33

[a]Subscripts of N, P, and K indicate kg/ha and subscripts of F indicate t/ha of farmyard manure.

Table 12. Rice yields from compost and chemical fertilizer applications, average from 1961-64.

Treatment	Grain yield (t/ha)		
	Rangsit	Surin	Pan
No fertilizer	1.37	1.7	2.53
Compost, 1.82 t/ha	1.61	2.16	2.50
Compost, 3.22 t/ha	1.90	2.43	2.74
Compost, 6.25 t/ha	2.16	2.53	2.82
Compost, 1.82 t/ha + NP[a]	1.75	2.87	2.87
Compost, 3.22 t/ha + NP[a]	1.62	2.74	2.74
Compost, 6.25 t/ha + NP[a]	2.33	2.94	2.94
NP[b]	1.60	2.82	3.02

[a]12.5 kg N/ha + 11 kg P/ha. [b]37.5 kg N/ha + 11 kg P/ha.

Table 13. Effect of farmyard manure application to rice in a rice-wheat sequence.

Treatment[a]	Rice grain yield 1977-79 (t/ha)
N_0F_0	3.15
N_0F_{12}	3.85
$N_{40}F_{12}$	5.16
$N_{80}F_{12}$	6.74
$N_{120}F_0$	6.62

[a]Subscripts of N indicate kg N/ha applied and subscripts of F indicate t/ha manure applied.

Studies on green manuring of rice by Williams et al (44) and Tiwari et al (39) suggest that N fertilizer efficiency diminishes when GM increases yields to near maximum. Experiments at IRRI show that at rice yield levels well below potential, contributions from green

Table 14. Available soil nutrients following 2 years of farmyard manure application to rice in a rice-wheat sequence, 12 t manure/ha applied per year.

Treatment	Organic C (%)	Available nutrient (kg/ha)		
		N	P	K
With FYM	0.300	164	12	170
Without FYM	0.229	111	8	151
Original	0.228	90	7	146
LSD (5% level)	0.034	16	1	7

manuring and inorganic N are additive (Fig. 11). Where full-term GM crops cannot be grown, the quantity of N that can be incorporated will be limited, in which case fertilizer N applications should be additive.

CONCLUSIONS

The effects of the peculiar nature of soil management for lowland rice on nutrient transformations, soil physical conditions, and soil profile development have implications for soil fertility and fertilizer management in rice-based cropping sequences. Although a few implications appear to be general, others require the accumulation of experience over a wider range of soil conditions and cropping sequences.

Nitrogen

For either rice or other field crops grown in sequence with rice, direct residual N benefits on the following crop are seldom significant. Where horticultural crops have received high N rates, the subsequent rice crop may benefit from residual N fertilizer or from N-rich crop residues.

Long-term studies of N balance show that where inorganic N is applied, soil N may increase or decrease depending on N rate, crops in the sequence, water management, and probably soil and climatic factors. Legumes exert a less negative effect than cereals on the N balance of a rice-based sequence. If the legume is incorporated as a GM, the effects may even be positive. Rice grain yield responses to 30- to 40-day-old fast-growing annual legumes incorporated before wet season rice are as high as 2 t/ha.

Because NO_3^- accumulates during fallow periods, yields from low or intermediate N rates applied to cereals grown in sequence with rice can be obtained by inorganic N applications to coincide with the period of greatest N uptake. This strategy is conditional upon inorganic N reaching the active root zone, either by placement or transport by infiltrating rain or irrigation water. This strategy assumes that soil N will be adequate to satisfy the early demands of

aerobically grown crops, recognizing that excessive early vegetative growth may not be desirable if N will be limiting during late vegetative and reproductive growth.

Phosphorus

Because chemical transformations increase P availability during rice cultivation, critical soil test P levels determined by common procedures are usually lower for rice than for other crops. On soils where P is required for rice and a crop grown in sequence with rice, residual P from an application only to the latter may also meet the requirement for rice. However, where rice yields are high and therefore the P requirement for rice is high, this generalization may not be applicable.

Potassium

With respect to K fertility, two factors peculiar to rice-based sequences may be important. Flooding increases the K concentration in soil solution, because exchangeable K^+ is displaced by the accumulations of NH^{4+} and Fe^{2+}. Whereas subsoil K contributes to aerobically grown crops, it probably does not do so to rice because its roots are concentrated in the surface 25 cm. There is little evidence of residual response by the following crop to inorganic K applied to either rice or the crop grown in sequence with rice. Residues of most crops contain a large fraction of the K accumulated by the crop, thereby contributing to the slow rate of soil K depletion. Where crops are grown in sequence with rice, those with high K requirements, such as maize, sweet potato, and tomato, may warrant preference for inorganic K applications.

Organic amendments and integrated fertilizer management

Crop residues, FYM, compost, and GM contribute variable amounts of N, P, K, and other nutrients to rice-based sequences, but these sources alone are not sufficient to maintain high yields in crops in intensive sequences. This is especially true for N, a nutrient that is lost from the system by denitrification, leaching, and volatilization as well as by crop removal. Empirical studies on a limited range of soils in warm climates suggest that organic amendments are most effective if incorporated before rice because anaerobic decomposition is rapid. In temperate climates, incorporation before upland crops in the rotation is reported most effective. The contrasting findings under the two climates appear to result from differences in the accumulation patterns of anaerobic decomposition products toxic to rice plants.

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WETLAND SOIL TESTS FOR CROP PRODUCTION

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More specificity is needed in the fertilizer recommendations made to farmers directly or through production programs. Grouping soils according to Soil taxonomy and using soil tests to separate within the groups can help improve the relevance of production programs to crop needs. It is well recognized, particularly in Indonesia, that relationships between chemical soil tests and yield levels (or yield responses) do not hold even across small distances. For example, the relationship between yield response to applied P fertilizer and chemical soil tests is not likely to be the same for soils developed from different parent materials, even though they may be in the same district. Some explanation for these differences can be given in terms of other variables, for example, clay type, pH, or organic matter content, or perhaps some of the more readily observable soil parameters.

Soil surveys have been widely used during this century to characterize and describe soils. They have provided a mechanism for laymen to appreciate soils as natural resources and for scientists to study soils more systematically. Soil tests can be used to give information both on the broad scale for land use planning and on the detailed level to guide extension workers and farmers concerning the appropriate use of fertilizers and soil amendments. But farmers and the agricultural community as a whole have not efficiently used the reservoir of information because the accuracy, detail, and availability of the reports do not always adequately meet users' needs.

Progress is being made in making soil survey information useful to farmers and to agricultural production programs. The comprehensive detail and organization incorporated in Soil taxonomy (7) permits

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on-farm usefulness for soil crop management purposes. Furthermore, Soil taxonomy provides the basis for transferring technology from one place to others with similar soil classifications. In this paper, we assume that valid information on climate, physiography, soil texture, mineralogy, depth, moisture regime, and other properties is available from soil classifications to various levels of detail (1). If we consider the users to be farmers and extension workers developing management practices for production programs, more information will be needed even though a soil survey can provide, in one document, much useful information.

The characteristics and uses of wetlands vary tremendously from place to place. Consequently, the kinds and precision of tests for characterization, diagnostic, and recommendation purposes also vary. With its wide range of soil conditions, management practices, and land uses, Indonesia provides a good cross-section of wetland soils that are found in other places in the world. We will use the Indonesian conditions for discussion purposes in this paper. In general, land areas in Indonesia are divided according to the edaphic conditions in the field (Table 1). They may be broken down further according to infrastructural development and management practices. Usually the land is owned and managed by small farmers; the average farm size on Java is less than 0.5 ha. Fertilizer and management practices suggested by extension programs are broad-based and not farmer-specific. More specificity is needed. In this respect, soil classification and soil tests -- from the general to the more specific -- can be of great value in making production programs more relevant to crop needs.

Table 1. Edaphic classification of agricultural land in Indonesia.

Edaphic conditions	Area[a] (million ha)	Most common soils
Upland rainfed areas		Ultisols, Inceptisols, and Oxisols
Humid		
Drought prone		
Lowland rice areas		
Irrigated	5.31	Entisols, Inceptisols, Vertisols, and Alfisols
Full	1.67	
Partial	3.64	
Rainfed	2.04	Aquepts and Aquults
Tidal swamp	0.24	Aquents and Aquepts
Direct		(Acid sulfate soils and potential acid sulfate soils)
Indirect		
Drained		
Freshwater swamp		Aquent, Aquepts, and Aquults

[a]Source: Soepraptohardjo and Suhardjo (3).

Soil scientists should consciously try to develop strategies to improve fertilizer efficiency and crop production in ways that will be acceptable to farmers. There have been dramatic improvements in rice yields in Indonesia over the past 15 years. Part of this increase has been due directly to varietal improvement. But much has been due to increased fertilizer use and improved crop management. Future increases will require a better understanding of soil-crop relationships. Strategies to make better use of soil classification and soil testing are needed to accomplish this goal.

MANAGEMENT TECHNIQUES FOR WETLAND RICE

The ability of a soil to hold water depends on its texture, mineralogy, and organic matter content. These soil properties, in combination, largely determine soil structure. The intensity with which soil water is held by the soil particles and the volume of the soil pores ultimately determine water availability in aerobic soils. But these same soil properties in flooded conditions determine the plasticity and the ease of puddling and manipulating soils. Several management techniques for wetland rice are followed in Indonesia.

Puddled lowland rice

Puddling of soil is a systematic process to reduce the soil structure and effective pore space and to minimize water movement. The objective is to retard water loss by percolation and to establish an anaerobic root environment. Puddling is a desired practice for lowland rice but may be detrimental to the production of the upland crops that follow. It tends to increase nutrient and water availability, control weeds, and moderate microclimatic changes.

Gogo rancah rice[1]

In cropping systems involving rice, several techniques may be used to increase cropping intensity. One of them is to plant earlier and use earlier-maturing varieties. With gogo rancah the rice is planted as soon as enough rain comes to permit land preparation, planting, and germination of the rice. Many times two crops can be grown where previously only one was grown. This practice does not work well on soils that are well drained and have a high infiltration rate; flooding in an unpuddled state allows excess water movement through the soil and loss of nutrients due to leaching. However, even on these soils gogo rancah can be grown successfully if the water table is maintained sufficiently high, either naturally or artificially.

[1] Indonesian term for rice which is dry seeded on aerobic soil and flooded about about 30 days after planting.

Walik jerami[2]

Removal and burning of rice straw are not good conservation practices. Straw residues must be returned to the soil to return soil nutrients and to maintain the organic content of the soil. Furthermore, rapid planting of a second crop after the harvest of the first saves time and water and provides the opportunity for intensified crop production. Transplanting a second rice crop without first plowing and cultivating the soil is called walik jerami. Usually the rice stubble and much of the straw and weeds are pushed into the soil by foot.

SOIL CHARACTERISTICS THAT AFFECT CROP MANAGEMENT

Some easily quantifiable soil properties that affect crop production may be further modified or affected by natural or man-made environmental factors. The following discussion includes some of the more common factors affecting soil-plant relationships that can be measured in various ways to provide guidance for management purposes.

Land form

The local landscape influences management practices directly, but it also plays an equally important geological role through the soil-forming processes. The existing soil and its characteristics represent an integration of all such effects over time. Two factors that are very important for crop and cropping systems management are drainage and water table. Even though these factors are related, effects for management are different.

Drainage. In addition to soil characterization, some evaluation of present natural and improved drainage and depth and frequency of flooding is useful for management purposes for lowland rice as well as for dryland crops that may be grown during the dry season. Many times new irrigation systems without adequate drainage do not significantly improve crop production and intensity.

Water table. The stability of dry-seeded rice (for uplands or for land that is later flooded) is closely related to the water table. The water table may be naturally perched, or continuous, or dependent upon the influence of irrigation water in surrounding areas. There is a similar effect, perhaps to a lesser extent, for rainfed lowland rice. The success of this cultural practice is dependent primarily upon rainfall and puddling of the soil, deficiencies of which cause the water table to affect crop production.

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[2] Transplanting a second crop of rice without plowing the soil.

Mineralogy

The management and productivity of many soils are directly affected by parent material, especially when there has been recent volcanic activity. However, the effects of time and composition of the volcanic effluent on the mineralogy of the soil are more important for soil and crop management purposes. A knowledge of the soil mineralogy, together with measures of the cation exchange capacity, indicates the crystallinity and activity of the soil's clay mineral fraction and their interaction with applied fertilizers.

The natures of the sand and silt fractions indicate drainage characteristics and determine the reserve supplies of nutrient elements in soils. Without these reserves, soils tend to be fragile and require more precise management techniques. Soils composed mostly of quartz are examples of infertile and fragile soils, and maintenance of their soil organic matter is critical.

The secondary clay minerals in soils affect nutrient availability directly through the exchange complex and through their intrinsic chemical composition. The retentive capacities of soils indirectly affect the availability of inherent and applied nutrients. Special management techniques are required at the extremes -- where the retentive capacity is nil or where fixation is strong.

Anomalies

Many times deficiencies in mineral nutrients are not as difficult to correct as excesses of some elements or soil components. These excesses need to be quantified, and some assessments must be made for corrective action. Special tests are needed, especially for diagnostic purposes.

Alkalinity. In drier areas alkalinity can be a major production problem because of the accumulation of Na in the soil-exchange complex. This may be a natural problem or a problem exacerbated by the high Na content of the irrigation water. This problem has been extensively studied and guidelines have been established for assessment and corrective action in the field.

Salinity. In drier areas or where seawater intrudes, the high salt content of soil and water may be a problem. Again, much work has been done to develop diagnostic and management techniques for this problem. However, remedial measures may be difficult and expensive to implement.

Acid sulfate. Many soils in tidally affected areas are covered with peat. Underlying the peat in many instances are potentially acid clays because of the presence of S compounds within the mineral soil. Upon drainage and oxidation, these soils become acid and have a pH between 3.5 and 4.0. The acidity of the soil depends upon the amount of S-bearing minerals (usually

jarosite) and the degree of oxidation of the soils. Management techniques have been developed by which the subsoil is kept in the reduced state. Consequently, drainage becomes a delicate and critically important management practice. Surface drainage is good and useful, but excessive drainage promotes oxidation and can produce situations in which the soil cannot support plant growth.

Deep peat. The value of peat for crop production depends upon its depth as well as its mineral content. Many peats in tropical areas are fibrous and deep (>1.0 m) and cannot sustain normal plant growth without major additions of nutrients. Shallow peats (<0.5 m), on the other hand, can be quite productive. Since peat soils are usually associated with acid sulfate, it is important that the soils remain anaerobic as much as possible. Rice can grow well under flooded conditions on these soils provided P fertilizers are applied. Farmers in Indonesia have developed an effective system of alternate furrow beds (± 6.0 m wide) and raised beds (± 2.0-4.0 m wide) to control water more effectively and to provide for food stability (the sorjan system). Rice is grown in the furrows while other food crops and later perennial crops are grown on the raised beds.

Low-exchange-capacity soils. Soils composed mostly of quartz sands (which may be clay size) and low-activity clays (such as highly ordered kaolinite and sesquioxides) have low exchange capacities. Mineral analysis can easily detect these soils, which have poor nutrient retention and require special attention.

AVAILABLE AND USEFUL TESTS

Various kinds of tests have been carried out to characterize soils to relate their properties to their potential to support plant growth. The mineral composition of the sand and silt fractions may be used as an indicator of the reserve nutrient status of a soil. Soil texture and clay mineral type may be determined to infer several physicochemical characteristics. Structure and other physical properties of a soil can assess tilth and water relationships. Organic matter and several chemical tests on reserve and available nutrients may be carried out to determine the fertility of a soil. Recommendations for fertilizers and soil amendments are often based on these tests, which may be grouped into three:

1. Tests used for characterization and diagnostic purposes,
2. Tests used for recommendation purposes, and
3. Tests used for both 1 and 2.

Different laboratories use different tests to make chemical evaluations. The tests belonging to the first group used in Indonesia are mineralogical tests; tests for texture, structure, and other physical properties; HCl (25%)-extractable P, K, Ca, and Mg; and CEC. Group 2 is composed of tests for available nutrients and Group 3 of tests for pH, organic matter, and exchangeable cation.

Mineral composition of sand and clay fractions

The mineral composition of the fine sand fraction is determined by counting each time a mineral passes through the cross bar of a microscope up to a count of 100. When minerals do not pass through the cross bar but are observed, they are graded as "trace." The percentage of a particular mineral is determined by the number of counts of the mineral. Identification of the mineral, for example biotite, would give an indication of the possible K resources.

Organic matter

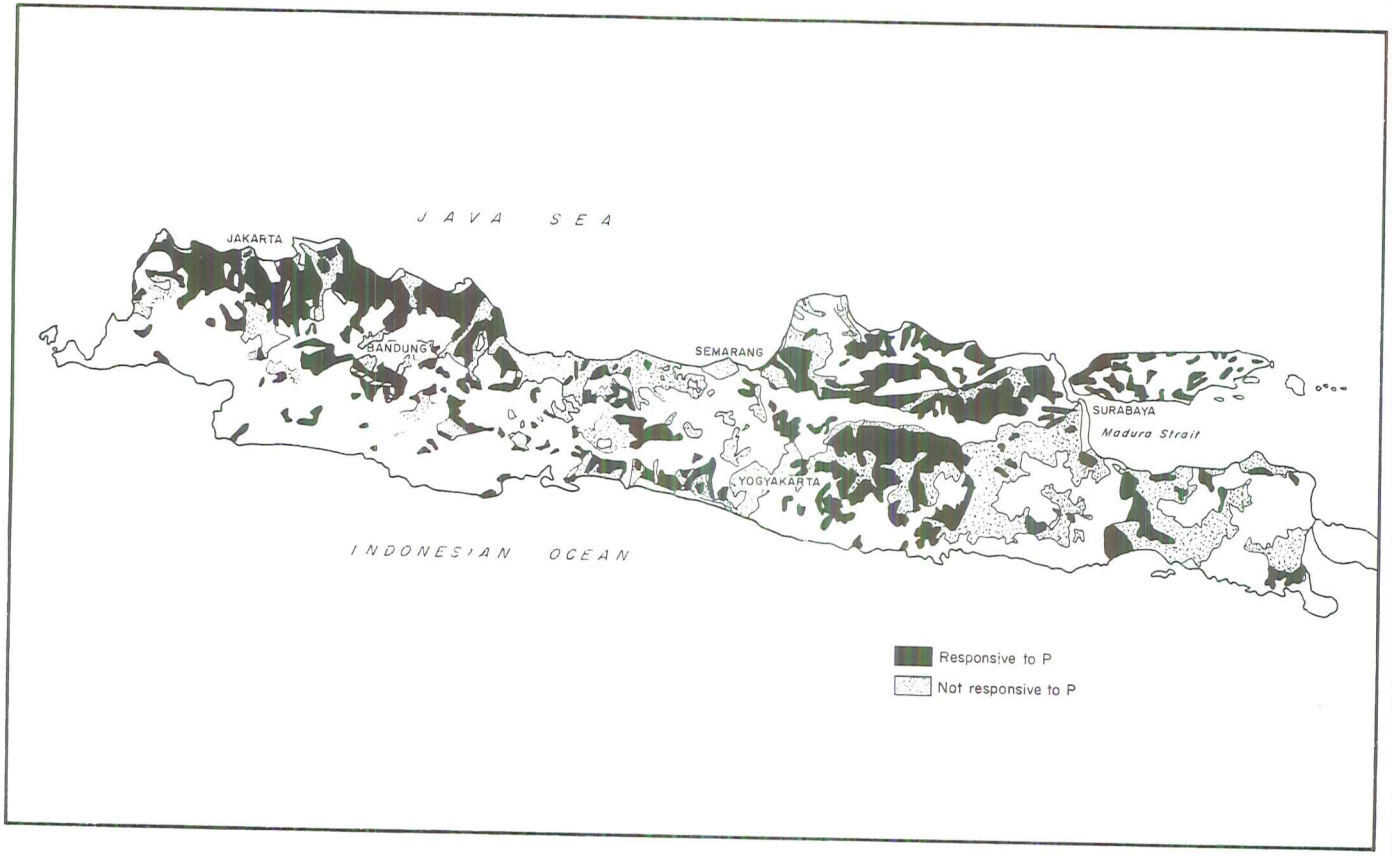
A wet combustion method is commonly used for organic C determination, and the Kurmis' modification has been used at the Center for Soils Research (5). Recently a colorimetric method has been used instead of the titrametric method.

Total N is usually determined by a procedure consisting of Kjeldahl digestion and steam or direct distillation. The C-N ratio is calculated directly from organic C and total N figures and can give a measure of the degree of breakdown of soil organic matter.

Chemical tests

Several chemical tests on reserve and available nutrients can be made to determine the fertility status of a soil. Twenty-five percent concentrated HCl-extractable P, K, Ca, and Mg are commonly used in Indonesia instead of the total to evaluate the reserve of nutrients in a soil. Crop characteristics, soil characteristics, and the existence of calibration data determine the use and interpretation of a soil test. In the case of P, the relationship between the chemically extractable level and yield response has to be recalibrated after the soil has received fertilizer applications.

Available phosphorus. Many extraction procedures have been proposed for wetland soils, including Bray-1, Olsen, and double acid, which are commonly used for dryland soils. The Olsen bicarbonate method has been increasingly adopted for paddy soils. Each procedure has its merit, but none are very useful until more data relating test results and yield responses are available. Figure 1 shows P responsiveness of soils on Java.



1. Phosphorus responsivity of soils on Java (4).

Exchangeable bases. Exchangeable K, Ca, and Mg are commonly extracted from soils by the: 1) double acid, 2) 1N NH_4OAc, pH 7.0, and 3) Morgan procedures. These extractions for exchangeable nutrients have good physicochemical bases for evaluating the nutrient availability in waterlogged paddy soil systems. For routine tests, one procedure should be selected and used over a wide enough area and length of time to develop correlations and ratings.

Available sulfur. Among the methods tested, the $Ca(H_2PO_4)_2$-extractable S gave the best correlation with S uptake and dry matter yield of rice in glasshouse experiments (6). The information, however, does not relate chemical-extractable S to field responses, as very few areas of deficiency have been delineated.

Micronutrients. The procedures and merits of several extraction methods for micronutrients have been adequately described for rice soils by Randhawa et al (2). Use of the DTPA-extraction method has been proposed in evaluating the availability of Zn, Mn, Fe, and Cu in soils (8). However, general recommendations for extraction procedures and interpretations cannot be made because sufficient correlation data have not been obtained over wide enough environmental conditions.

Physical tests

Several measurements may be made to assess the physical properties of paddy soils, including texture and permeability, water retention, water table, hydromorphic qualities, compactability, aggregate stability, Atterberg values, and soil depth. The following measurements are commonly used in our laboratories for samples received.

Texture. A field determination of soil texture is done on all samples. This classification is supported by a laboratory determination of mechanical analysis. The pipet method is usually used at the Center for Soils Research laboratory. The texture and structure of a soil determine its tilth and air-water relationships. Soil structure is subjectively observed and qualitatively evaluated in field. Pore size distribution is inferred from bulk density, particle density, and the water retention (pF) curve of a soil.

Bulk density and pore space. Bulk density is determined using undisturbed samples. Total pore percentage is calculated using the following formula.

$$\text{Total pore percentage} = \left(1 - \frac{\text{Bulk density}}{\text{Particle specific density}} \times 100\right)$$

For mineral soils the particle density is assumed to be 2.65. If the soil organic matter is more than 1% the particle density is reduced by 0.02 for every 1% increase in organic matter of the mineral soil.

Water retention. The water retention (pF) curve is determined by measuring the weight of moisture retained by a 1-cm thick sample of undisturbed soil at pF values of 1, 2, and 2.54 using a moisture plate apparatus.

Permeability. Soil permeability depends upon pore size distribution and form, which in turn are affected by the texture and structure of the soil. Soil permeability is measured under saturated conditions using Darcy's law. Aggregate stability is measured by weight differences for samples of a certain aggregate diameter between wet and dry sieving.

STRATEGY

Various kinds of tests have been developed for wetland rice cropping systems. These tests are used extensively for diagnostic purposes; they have not been widely used for routine analysis of farmers' soil samples. There is a need to make better use of these tests to make more efficient use of labor, water, and fertilizer inputs.

There have been dramatic increases in the production of wetland rice over the past 15 years, particularly in Asia. Much of the increase in yield has been arbitrarily attributed to varietal improvement. However, there have been a concomitant improvement in agronomic practices and increased fertilizer use. Production programs, particularly in developing countries, have been very effective in promoting better management practices and in providing credit for inputs. These programs have usually started without much of a specific technological base; recommendations have been broad-based. Gradually, technology and procedures have been developed to make recommended practices fit the local soil and climatic environments.

It is time soil scientists and agronomists develop integrated and more systematic research procedures so that technology may be developed to meet the specific needs of farmers or farmer groups. But first, better use should be made of existing information and technology. The following strategies should be followed:

- Existing broad-based soil classification systems should be used to delineate edaphological conditions that require different management practices.
- Specific soil classification systems such as Soil taxonomy should be used to characterize soil conditions more precisely. This information may be extrapolated over a wider area with a minimum of test sites.
- Special soil conditions or anomalies that exist within the delineated areas will require more detailed and specific studies.
- A series of experimental fields or field test sites may be used or established to study on-

site conditions in more detail. The studies would include detailed soil descriptions, soil fertility/crop response trials, and soil test correlation studies over long enough periods of time to assess stability and sustainability of crop production.

- These studies must be carried out in close collaboration with extension specialists who finally develop and implement production programs to effect a smooth transfer of technology. However, use of the technology should not preclude or delay publication of the results in national and international journals. Better mechanisms for publishing incomplete studies are needed, particularly for long-term studies.

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CLASSIFICATION OF WETLAND SOILS

WETLAND SOILS OF THE WORLD, THEIR CHARACTERIZATION AND DISTRIBUTION IN THE FAO-UNESCO APPROACH

C. A. VAN DIEPEN

Two concepts of wetlands are distinguished: a genetic concept such as is used in the FAO-UNESCO Legend (6) for the definition of hydromorphic properties, and a utilitarian concept that would be more suitable for use in land evaluation. The place of hydromorphic soils in the FAO-UNESCO Legend is discussed, and possible amendments to the Legend are mentioned. Suggestions are made for the characterization by means of a hydrograph of soil wetness regimes for land evaluation purposes. Possibilities for inventorying hydromorphic soils on the basis of the FAO-UNESCO Soil map of the world (5), with and without application of map unit composition rules, are evaluated. There is a need for elaborating the Legend and updating the Soil map of the world in such a way that it can be used as a data base for the computer-assisted appraisal of land resources.

The meaning of the American English word "wetlands" given in Webster's New Collegiate Dictionary is "land or areas as tidal flats or swamps containing much soil moisture." This description clearly refers to permanently wet, flat landscapes. But in pedology it is probably more meaningful to define wetlands in terms of moisture regime only. This means that wetland soils are not, by definition, confined to low-lying landforms such as floodplains, deltas, and depressions, but may also occur on higher parts of the landscape like river terraces, footslopes, and even the tops of hills.

In a general way, a distinction can be made between two possible definitions of wetlands: one related to use and use possibilities of the land, which may be called a utilitarian definition, and one related to soil genesis (soil formation), which may be called a genetic definition.

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These concepts can be described as

- wetland soil, utilitarian concept: a soil subject to periods of excessive wetness to the extent that it greatly influences the soil's use possibilities, and
- wetland soil, genetic concept: a soil that bears marks of its formation under wet, reducing conditions, notably gray colors and mottling.

In practice there is considerable overlap between the two definitions, but they are not identical. The utilitarian definition excludes hydromorphic soils that are not subject to prolonged water saturation such as artificially drained floodplains in use for growing upland crops. The genetic definition excludes soils that are subject to waterlogging but show no morphologic evidence thereof, such as young alluvial soils and upland soils recently used for wet rice-growing.

The utilitarian concept is probably the most meaningful for land-use planning purposes. However, because no soil wetness classification system or world soil wetness inventory exists, systematic information on soil wetness cannot be readily obtained.

The choice of a definition depends also on the scope of the study in which it is used, and on the source of information on which it is based. For the occasion of the Polders of the World congress, ISRIC recently made a study of the distribution and agricultural potential of the world's wetland soils (18). The study focused on the soils of those flat wetlands where the improvement of internal drainage would lead or had already led to an increase of agricultural productivity. The quickest and cheapest way to complete this utilitarian-type of inventory was by interpreting the FAO-UNESCO Soil map of the world at scale 1:5 million (5, 6), in spite of the genetic nature of the definitions of its soil units.

WETLAND SOILS IN THE FAO-UNESCO LEGEND

Like most soil classification systems, the FAO-UNESCO Legend (6) is genetic in approach. As a consequence, no distinction is made between present soil wetness regimes and relic features of past wetness regimes. Also, features of wetness are not viewed in isolation but in conjunction with other soil properties whereby the relative importance of a given wetness regime is weighted differently for different soil units. This means that the wetness regime alone cannot be used as an entry for singling out wetland soils from the soil map legend and that one has to resort to deductions in cases where the wetness regime is not specified.

For practical reasons, the best choice as counterparts of wetland soils in the FAO-UNESCO Legend is probably: "soils showing hydromorphic properties within 50 cm of the surface," which means showing morphological evidence of waterlogging and reduced conditions within 50 cm. This corresponds to the definitions of aquic suborders of Soil taxonomy (17). However, it is a common misinterpretation that the Legend places all soils with hydromorphic properties in one group. The Legend makes a hierarchical distinction between weakly developed soils that are strongly influenced by groundwater, the Gleysols, and soils that show strong groundwater influence in combination with strong profile development, the "gleyic" groups.

The above definition of wetland soils applies directly to Gleysols (Aquents, Aquepts), Histosols, and the gleyic groups of other units, because by definition they all have hydromorphic properties within 50 cm of the surface. An exception forms the Gleyic Cambisol unit (aquic subgroup of Ochrepts) in which hydromorphic properties appear below 50 cm but within 100 cm of the surface.

Some other soil units may or may not have hydromorphic properties within 50 cm and therefore cannot be subdivided into part wetland soils and part nonwetland soils. In ISRIC's inventory (18), they have been placed in the wetland category. They include Fluvisols, Planasols, and Pellic Vertisols.

Fluvisols (Fluvents) do not necessarily have hydromorphic properties, but most of them are regularly flooded under natural conditions. Hydromorphic Fluvisols differ from Gleysols in that they have fine stratification or irregular decrease of organic matter with depth, or both. In fact, both soil units are often confounded, and even the Soil map of the world project has failed to separate them systematically during the mapping of the floodplains and deltas of the larger rivers.

Planosols are wetland soils in the genetic sense (stanogley soils). They correspond partly with Albaqualfs and Albaquults, partly with the pale-great groups of Alfisols or of Argialbolls. The 50-cm depth limit does not apply because the Legend stipulates that Planosols have hydromorphic properties at least in a part of the E horizon, while the E horizon may extend down to 125 cm from the surface. The same applies to the plinthic groups of Ferralsols (Oxisols), Acrisols (Ultisols), and Luvisols (Alfisols), which are defined on the basis of having plinthite within 125 cm of the surface, while in the key to the soil units, the plinthic groups take precedence over the gleyic groups. The same situation applies to the Placic Podzols in relation to the Gleyic Podzols. Like the Planosols, the

plinthic groups and Placic Podzols are genetically wetland soils, many of which show their hydromorphic properties within 50-cm depth.

Also, the position of the Pellic Vertisols in relation to the wetland soils cannot be judged from their definition, because hydromorphic properties are not a requirement. In reality many Pellic Vertisols are close to meeting the diagnostic soil color criterion for hydromorphic properties and could therefore be considered wetland soils.

POSSIBLE AMENDMENTS TO THE FAO-UNESCO LEGEND

The FAO-UNESCO Legend counts 106 soil units, which have been clustered into 26 major groupings. There are two categorical levels: major soil units (comparable to orders) and soil units or groups (comparable to great groups). The Legend has been specifically made for a 1:5,000,000 soil map. If it is to serve as a basis for an internationally accepted soil classification and nomenclature, such as the International Reference Base for soil classification (IRB), the Legend has to be elaborated on to some extent. In relation to the classification of hydromorphic soils, the following points need attention.

The number of gleyic groups could be increased to make the Legend more systematic. From the 26 major soil units, 9 have a gleyic group. The absence of gleyic groups in the other major units is due to various reasons, of which we mention a few:

- The limited geographic importance at the global scale, or scattered distribution of a missing gleyic group, would not justify its representation on the map as a separate unit. Or knowledge of its distribution at the global scale was sufficient that it could not be separated systematically.

  A soil that actually belongs to a conceivable but not defined soil unit now, according to the Legend, either is placed in another unit or can simply not be properly classified. As examples:

  - a Gleyic Regosol and a Gleyic Arenosol meet the definition of a Gleysol;
  - A Gleyic Nitosol and a Gleyic Andosol are not foreseen;
  - a Gleyic Chernozem without an argillic horizon meets the definition of a Mollic Gleysol, while a Gleyic Chernozem with an argillic horizon is not foreseen.

- If hydromorphic properties are already implied in the definition, as is the case of Histosols, Gleysols, and Planosols, a distinction of gleyic groups would in fact not add much information on the kind of soil.
- For some soil groupings, the hydromorphic properties, if present, are considered less important than other soil properties. This is the case with Vertisols, Fluvisols, and Ferralsols. Perhaps intergrade groups such as Gleyo-Dystric Fluvisol and Gleyo-Pellic Vertisol can be introduced.

There are also arguments for making the system internally more consistent by assigning the term "gleyic" the same meaning and by using it at the same categorical level throughout the Legend, and by using it also if hydromorphic properties are only implied. The uniform meaning of "gleyic" would become: having hydromorphic properties within 50 cm of the surface. It would, however, break up at the present system. In particular, the Gleysol unit would fall apart. Other definitions in the present Legend that would need to be changed are as follows:

- Gleyic groups are not distinguished in Planosols and Fluvisols.
- Gleyic groups of Greyzems and Phaeozems indicate hydromorphic properties within 50 cm in the presence of an argillic horizon.
- Gleyic in relation to Cambisols means hydromorphic properties appearing between the 50- and 100-cm depths.

Such uniformity may seem superfluous to many soil correlators, but it would certainly be helpful in communicating with nonsoil people.

Other aspects of hydromorphic properties requiring systematization include various forms of pseudogley (or surface gley) and groundwater gley, alone or in combinations.

Pseudogley is the kind of hydromorphism related to periodic saturation and reduction in the upper part of the profile, while the lower part remains aerated. Stagnogley is an extreme form of pseudogley formed under permanently wet conditions (15). Morphologically related with pseudogley are the surface gley phenomena in paddy fields (see below).

Gley, as used in contrast to pseudogley, refers to groundwater gley phenomena. The type of gley depends on the depth and fluctuation of the water table:

- Anmoor gley or humic gley if the groundwater is permanently near the surface;
- Gley or mineral gley if the groundwater fluctuates at shallow depth. Many intermediate types such as semigley and pseudogley over amphigley may be distinguished (2).

Differences in character between groundwater gley soils and pseudogley soils require a different position in soil systematics (15), but in the FAO-UNESCO Legend and in the US Soil taxonomy such a distinction has still to be worked out.

As in Soil taxonomy, no special provisions are made in the Legend for the classification of naturally freely draining soils that have a gleyed surface horizon as a result of long-lasting wet rice cultivation. It is probably desirable to separate these paddy soils from their well-drained counterparts, for which the term "anthraquic" (3) or "aquorizemic" (10) seems appropriate.

The classification of two pairs of soil profiles from Japan, which form part of ISRIC's soil monolith collection (12), may serve as an example. The four soils all have a deep groundwater table and high permeability. One pair of soils was formed in alluvial material and one pair in volcanic ash. Each pair comprises a paddy soil and an adjacent nonpaddy soil. The Fluvisol paddy has been used for the production of rice for 55 years, the Andosol paddy for about 200 years. Their (tentative) classifications are indicated in Table 1.

CHARACTERIZATION OF SOIL WETNESS FOR LAND EVALUATION PURPOSES

For land evaluation purposes, knowledge of the present and possibly the future soil wetness or soil moisture regimes is necessary. The notion of hydromorphic properties within a 50-cm depth is too vague for any quantitative assessment, because it gives no information on the duration, depth, and fluctuations of the groundwater table. It has been found many times that mottling could not be related to the length of the periods of water saturation (19).

Table 1. Classification of ISRC soil monoliths from Japan.[a]

Classification system	Alluvial		Volcanic	
	Nonpaddy soil (monolith J4)	Paddy soil (monolith J3)	Nonpaddy soil (monolith J2)	Paddy soil (monolith J1)
FAO-UNESCO	Dystric Fluvisol	(Anthraquo[a])-Dystric Fluvisol	Humic Andosol	(Ando)-Dystric Gleysol or (Anthraquo[b]-Ochric Andosol)
USDA	Typic Udifluvent, fine, mixed, non-acid, mesic	(Anthraquic Udifluvent, fine, mixed, nonacid, mesic	Typic Dystrandept, coarse loamy, mixed, mesic	Typic Haplaquent, coarse loamy, mixed, nonacid, mesic
Japan	Brown lowland	Brown lowland	Ando	Gleyed Andosol

[a]Source: Okazaki (11). [b] or "aquorizemo."

This situation calls for an autonomous characterization of the soil wetness regime, completely apart from the classification of the soil proper. The design of classes of wetness regimes should be left to the national or regional organizations in the first instance, but preferably on the basis of some standardized concepts. To be meaningful for land evaluation, separate criteria for class subdivisions should be developed for such different kinds of land use as wetland rice and dryland crops.

The most important elements for the agricultural evaluation of soil wetness are the depth and fluctuations of the groundwater table and the duration of wet conditions in the rooting zone. One may also read, instead of a groundwater table, "perched groundwater table" or "depth of flooding or ponding," whichever is applicable.

The wetness of a soil can be characterized at any moment by the depth of the water table. Here, wetness is used in the technical sense of the word. This technical concept is more operational than the genetic concepts of hydromorphic properties used in the FAO-UNESCO Legend and the definitions of aquic moisture regime and aquic suborders according to Soil taxonomy. In this respect, wetness need not result in reducing conditions, last at least a few days, or be a result of irrigation. Also, wetness in artificially drained soils is determined by the depth of the groundwater table, independent of past wetness regimes.

The soil wetness regime over a year or a season can be conveniently represented by a kind of a hydrograph showing water level under or above the ground surface versus time. The hydrograph shows the depth, duration, and nature of fluctuation of the groundwater and flooding regimes, including extreme values. The hydrograph could be used as an accessory characteristic of wetland soils and of other soils that are periodically partly or completely wet.

A "wetness regime classification" may bring some order to the thousands of possible different hydrographs. The distinction into types of wetness regime should be based on an understanding of their causes and their implications for the use of the land.

If only groundwater is concerned, a simple classification can be made on the basis of the average highest and lowest groundwater levels within a growing season, as is reported from Nigeria to characterize the wetness regime along a valley catena (19).

However, if flooding occurs, more attention should probably be paid to the shape of the hydrograph: smoothness, peaks, gradients of falling and rising sections, and duration. Also, the variations over the years, the occurrence of catastrophic events, and

possibilities of manipulating the wetness regime by drainage, irrigation, and flood control measures have great influence on land use possibilities.

DISTRIBUTION OF WETLAND SOILS

The distribution of wetland soils, or rather of hydromorphic soils, has two aspects: the geographic pattern of occurrence and the total area.

The pattern of occurrence of hydromorphic soils is closely related to physiography and climate. Naturally, the soils are found in places where the land's drainage capacity falls short of evacuating the water surplus over evaporation. The water surplus originates from rainfall, surface runoff, and groundwater flow. In general, hydromorphic soils are most widespread in high-rainfall areas and at the lower ends of toposequences. They are also very common in cold regions.

Considering individual soil units, Fluvisols and Gleysols occur in the floodplains and estuaries. In dry regions these soils have often turned into Solonchaks. In landforms situated somewhat above the present floodplain level such as terraces and erosion surfaces, the soils have been exposed to soil-forming processes for some period. If drainage is or has been impeded, gleyic groups are found. In subhumid climates, they are often Gleyic Luvisols. Under warm climates with seasonally alternating wet and dry soil conditions, Planosols are also widespread; under warm and humid conditions, Gleyic Acrisols develop. Pellic Vertisols occur commonly in wide depressions in the tropics and subtropics with a marked dry season. Histosols are typical for swampy areas under any climatic regime, but are most widespread in cold climates.

It is with a certain reluctance that we give figures on the extent of wetland soils (Table 2). First of all, such figures are not accurate because of the coarseness of the map (very small scale); secondly, such figures are easily misinterpreted. But for comparison, some totaled figures of ISRIC's wetland soil inventory (18) are given. At the time of the study, the extents of individual soil units were not yet computerized, and the areas were measured on the map and totaled using a pocket calculator. The areas were broken down by soil unit, by each of the nine major regions (continents), and by length of temperature-determined growing season, and were separated for aridic and nonaridic zones. Low-potential wetland soils, which cannot be improved by better water management -- for example, the coastal peat soils of Sumatra and Kalimantan, and the permafrost zone -- were excluded from the inventory. On the other hand, saline soils and alluvial soils in deserts were included

Table 2. Extent of flat wetlands (naturally hydromorphic-level soils) suitable for agriculture if good water management is provided.[a]

Major region	Extent (million ha) suited for			
	General agriculture		Rice	
	Total	Within aridic zones	Total	Within aridic zones
North America	104	3	50	1
Central America	26	1	26	1
South America	253	36	222	14
Europe	144	4	21	2
Africa	200	46	200	46
South and SW Asia	105	54	105	54
North and Central Asia	278	63	107	29
Southeast Asia	89	–	89	–
Australasia	52	13	50	13
World total	1251	220	870	160

[a]Source: van Dam and van Diepen (17).

because in such soils water is the limiting factor, not the soil, so that their development potential has to be interpreted from a water resource study.

THE SOIL MAP OF THE WORLD AS DATA BASE

A map unit of the Soil map of the world represents a physiographic entity, or landscape, large enough for its delineation on the map, on which it is registered by the color and the symbol of its dominant soil unit, followed by a reference number. The composition of each map unit is described in terms of dominant soil, associated soils, and inclusions.

The Legend stipulates that associated soils cover at least 20% of the area and inclusions less than 20%. This statement is not sufficiently specific for the purpose of calculating areas of individual soil units on the basis of the composition of the map units. Such a conversion of map units into soil units has been achieved by FAO's Agro-ecological Zones Project (7) by applying fixed "mapping unit composition rules" to the computerized list of map units.

These rules (Table 3) were fixed only after the map was completed. They imply that a dominant soil occupies between 24 and 100% of the map unit's area, depending on the map unit's composition. Ratios of a dominant to a subdominant soil larger than 70/30 are not foreseen in the rules. Such high ratios are, however, not always negligible, particularly for regions where agriculture is concentrated in relatively small portions of fertile land amid large stretches of marginal land.

Table 3. Relative distribution of dominant soil, associated soil(s), and inclusion(s), expressed in percentage of the area of the mapping units.[a]

Dominant soil area (%)	Associated soil(s)		Inclusion(s)	
	Soil units (no.)	Area (%)	Soil units (no.)	Area (%)
100	0	0	0	0
70	1	30	0	0
60	1	30	1	10
60	2	20 + 20	0	0
50	2	20 + 20	1	10
30	3	20 + 20 + 20	1	10
50	1	30	2	10 + 10
40	1	30	3	10 + 10 + 10
50	1	30	4	5 + 5 + 5 + 5
40	2	20 + 20	2	10 + 10
30	2	20 + 20	3	10 + 10 + 10
30	3	20 + 20 + 20	2	5 + 5
25	3	20 + 20 + 20	3	5 + 5 + 5
24	3	20 + 20 + 20	4	4 + 4 + 4 + 4

[a]Source: FAO (7).

To improve the situation, the composition of mapping units should be reassessed, specifying the proportional occurrence of soil units in each map unit as it is, to replace the fixed composition rules. The collection of such additional data would require a huge effort, but the use of a computerized mapping unit file would permit storage and effective handling.

For the purpose of inventorying the hydromorphic soils of the world, we may distinguish the hydromorphic map units from the freely draining map units.

The extents of hydromorphic soils in Table 2 are obtained through measurements of the map of the predominantly hydromorphic map units. This procedure is prone to underestimation and overestimation, because it overlooks the intermingling of hydromorphic and freely draining soils. The areas of hydromorphic soils obtained through simple measurement on the map appear much lower than those calculated with the mapping unit composition rules. For example, for the African continent, a ratio of 1:1.7 was found. Africa's land surface represented by predominantly hydromorphic map units is 7.2% of its total land area, while the total extent of hydromorphic soils, calculated on the basis of the map unit composition rules, is 12.1%. These hydromorphic soils are distributed over the classification units as follows: Gleysols and Fluvisols together, 66%; Pellic Vertisols, 16%; Gleyic Luvisols, 7%; Planosols, 4%; Histosols, 3%; Gleyic Solonchaks, 2%; and Gleyic Acrisols, 1%.

The scale of the Soil map of the world is 1:5 million. It does not allow the separation of single areas smaller than 250 km^2 (2 x 5 mm on the map) or narrower than 5 km (1 mm on the map). This means that

on the scale of a continent, only the largest concentrations of hydromorphic soils appear on the map, where they occur in the bottom of large basins and in the lowland areas at the edges of the continents.

In reality, however, hydromorphic soils also occur as patches and strips in the map units with predominantly freely draining soils. Theoretically their extent could be calculated from the map unit composition rules for associated soils and inclusions, but in practice their occurrence has been overlooked in many cases largely because of the emphasis on mature zonal soils in the exploratory and reconnaissance type of soil maps on which the Soil map of the world is based. On such maps, azonal soils are shown only where they are dominant over large areas, and little attention is given, for instance, to valley bottom soils within upland regions. This may be justified on the basis of their lesser geographic extent, but if the economic and ecologic importance of hydromorphic soils is taken into account, they should at least receive as much attention as their more extensive freely draining counterparts.

So, mapping constraints, together with a bias toward freely draining upland soils, lead to an underestimation of the extent of hydromorphic soils. This results in the tendency, on different soil maps of a given region, for the area of hydromorphic soil units to increase with increasing map scale. Two examples, one from China, where the wetlands are exploited to the maximum, and one from Africa, where the wetlands are a relatively underdeveloped resource, may illustrate this tendency.

The uplands and plateaus of southcentral China, indicated as the red earth region on the Soil map of China (13) appear on the Soil map of the world as sloping Orthic Acrisols in association with Lithosols (Ao13-bc) or with both Lithosols and Chromic Luvisols (Ao18-bc). No mention is made of hydromorphic soils. Soil maps at a scale of 1:100,000 of 259-km^2 sample blocks in this region (8) show dissected landscapes in which reducing, redoxing, and oxidixing paddy soils together occupy some 20-40% of the total area.

The example from Africa concerns the northwestern Ivory Coast, where the Soil map of the world shows a map unit of Dystric Nitosols associated with Plinthic Acrisols and Lithosols (Nd27) and a map unit of Ferric Acrisols associated with Orthic Acrisols and Dystric Nitosols (Af 5). No hydromorphic soils are indicated. A series of maps of the same area exists at scales increasing from 1:2 million to 1:200,000, with maps of selected sample landscapes at 1:50,000 (1, 14, 4). The position of the hydromorphic soils on these maps of the area corresponding to both FAO map units is as follows:

- The 1:2 million map (1) gives a rough idea of soil regions and shows 3% hydromorphic soils.
- The 1:500,000 map (14), used for the compilation of the FAO map, shows 9% alluvial soils, roughly sketched on the map.
- The 1:200,000 map (4) shows about 11% alluvial soils in a much finer pattern.
- The 1:50,000 map (4) shows the next order branches of the valley system and separate flood-plain soils from lower slope soils. Together they occupy 17% of the sample area in FAO's Nitosol unit and 29% in the Acrisol unit.

The foregoing examples show the complete omission of hydromorphic soils from the map units, but other examples in which they occur and where their calculated extent corresponds with information from more detailed soil maps can be cited. For instance, the 10% cover of Eutric Gleysols included in map unit Lf49 in southwestern Nigeria is equal to the estimate of the land facet study at a scale of 1:125,000 in which sample strips at a scale of 1:10,000 (11) were used.

Inventorying hydromorphic soils in areas where they are subdominant is hazardous, whether it is done on the basis of the Soil map of the world or on the basis of other general-purpose soil surveys. The large margins used in wetland distribution studies become apparent in the results of the wetland inventory in the coastal countries of West Africa (9). The wetland area is estimated at somewhere between 12.6 and 28.5% of the total area. The four types of wetlands and their estimated distribution as percentages of total area are

• deltas, tidal swamps, and large inland swamps	1.7 - 3.5%
• river floodplains (large floodplains)	2.5 - 5.9%
• overflow valleys (small floodplains)	3.6 - 9.0%
• streamflow valleys (small inland valleys	4.7 - 10.0%

The wetlands of the smallest-size category represent the largest total extent. That means that a large part of the West African wetlands cannot be shown by normal cartographic means on an exploratory type of soil map even at a scale of 1:1 million, which is generally considered the maximum feasible for world maps (16).

A realistic appraisal of the world's wetland soils will require the updating of the FAO-UNESCO Soil map of the world. Several lines of action may be taken concurrently:

- increase of map scale from 1:5 million to 1:1 million, making the map surface 25 times larger, thereby bringing the smallest mapable area from

250 to 10 km^2. A larger number of floodplains could be put on the map, but many wet soils would still have to be included in other map units;

- improvement in the cartographic delimitation of map units;
- specific estimates of soil composition of individual map units;
- elaboration of the Legend, e.g., through the approach of the International Reference Base for soil classification (IRB);
- computerization of the soil data base: mapping unit file, pedon data file, crossing of the map such as with overlays; and
- special attention to the definitions of wetness regimes, independently of soil units. The separate treatment of wetness and soils is to be preferred, because a combined subdivision can never completely represent satisfactorily the many differences in flooding-submergence-groundwater regimes. Separate treatment allows greater flexibility for adaptation of both soils and wetness definitions and is more suited for computer-assisted data handling.

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CLASSIFICATION OF WETLAND SOILS IN SOIL TAXONOMY

H. ESWARAN and T. COOK

Unlike other classification systems, Soil taxonomy (4) does not provide a single class at the highest categoric level for wet soils. Depending on the wetness state and duration, the wetness attribute is brought in at different categoric levels in each order. The aquic suborders and subgroups express one kind of wetness in most orders. Intergrades to the wetness condition are expressed through classes such as aeric and epiaquic. In some taxa, terms such as pachic, cumulic, and vertic are used; the wetness condition is implied to some extent and so is not spelled out in the definition. The paper also indicates some inconsistencies in some definitions and reviews suggestions for other modifications. A dasyk pan and an anthraquic horizon are defined and their placement in Soil taxonomy is presented as a proposal.

Water-saturated soils have had a special place in the classification of soil series, or of the ecosystem, or indirectly in the classification of plant and animal communities. These ecosystems have been of prime concern to ecologists because of their very fragile nature, and many attempts have been made to define them. Recently, the U.S. Department of the Interior (1) developed a definition and classification of wetlands:

> Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For purposes of this classification wetlands must have one or more of three attributes:
>
> 1. at least periodically, the land supports predominantly hydrophytes;
> 2. the substrate is predominantly undrained hydric soils; or
> 3. the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

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As is evident, the definition focuses on the ecosystem and includes:

- areas with hydrophytes and hydric soils such as those commonly known as marshes, swamps, and bogs;
- areas without hydrophytes but with hydric soils e.g., flats where drastic fluctuations in water level, wave action, turbidity, or high salt concentration may prevent the growth of hydrophytes;
- areas with hydrophytes but nonhydric soils such as margins of impoundments or excavations where hydrophytes have become established but hydric soils have not yet developed;
- areas without soils but with hydrophytes such as the seaweed-covered portion of rocky shores; and
- wetlands without soils and without hydrophytes such as gravel beaches or rocky shores without vegetation.

From the soils point of view, the above definition deals with only one kind of wet soil. Drained soils that are now incapable of supporting hydrophytes are not considered wetland soils. At the other extreme, long-term management, as for rice cultivation, may induce wet soil conditions, and such soils are also excluded in this definition.

Consequently, the Soil Conservation Service of the U.S. Department of Agriculture (unpubl. National Bulletin No. 430-2-7) developed the concept of hydric soils. The definition follows.

Hydric soils have either:

- soil that is saturated at or near the soil surface with water that virtually lacks free O_2 for significant periods during the growing season, or
- soil that is flooded frequently for long periods during the growing season.

Although not spelled out in the definition, this adheres to the concepts in Soil taxonomy (4) and uses accessory properties of soils to infer hydric conditions. In describing and classifying soils that are most directly related to conditions characteristic of wetlands, the morphological properties that are routinely observed are gray colors, the presence of Fe and Mn concretions near the surface, and wetness. In addition, position in the landscape, known history of flooding or ponding, and evidence of natural or man-made alterations of the natural moisture regime are also used as aids in field identification of hydric soils.

Practically all soil classification systems provide a special class for the saturated soils and provide for intergrades to the less wet members or

those that show only periodic wetness. Soil taxonomy differs from all other classification systems by handling wetness in a completely different manner. The purpose of this paper is to elaborate on the concepts employed in Soil taxonomy and not only to show how wet soils are classified but also to indicate some problem areas.

SOIL MOISTURE REGIMES

Unlike the concepts of wetlands and hydric soils, which imply moisture saturation during some time of the year, soil moisture regimes denote the condition of the soil with respect to the tension at which moisture is held over a specific depth or control section and the period of the year during which the moisture state or states is maintained. The critical tensions are 15 bars, which is equivalent to the wilting point, and 1/3 bar, which simulates field capacity. The moisture control section is considered dry if it is at or above 15 bars, partly dry or partly moist if it is between 15 bars and 1/3 bar, and moist if it is at less than 1/3 bar. The different kinds of soil moisture regimes are defined in relation to the period at which the control section is at one or at two of these moisture conditions and, more importantly, in relation to the soil temperature regime at the time of these conditions. The summer and winter solstices are used as reference points for determination of the soil moisture regimes.

Five soil moisture regime classes -- aridic, ustic, xeric, udic, and perudic -- are identified and their definitions are given in Appendix 1. Figure 1 schematizes the different soil moisture regimes in reference to the number of days the moisture control section is dry or partly dry. Determination of the actual moisture regimes requires field measurements over a long period of time. Such data are not readily available. A first approximation could be obtained through an unpublished computer simulation model developed by Franklin Newhall, which has been slightly modified by A. Van Wambeke (5). Figures 2-5 are the results of such a model applied to five stations that illustrate the five moisture regimes.

When reducing conditions, due to water saturation, prevail for long periods of time, a special soil water regime is defined. This is termed the aquic soil moisture regime. These soil moisture regimes (except the perudic soil moisture regime, which is only used indirectly) and soil water regimes are used to define classes (or taxa) in the various categories of the system.

Cumulative time Soil Moisture Control Section (SMCS) is moist [a/]

1/4 yr (91 d)	1/2 yr (183 d)	3/4 yr (274 d)	1 yr (365 d)
Some part of SMCS ARIDIC or TORRIC	Some part of SMCS USTIC	All parts of SMCS UDIC	
or XERIC if Moist 90 consecutive days when soil temperature at 50 cm > 8°C and For 45 consecutive days in all parts SMCS during the 4 mo after 22 Dec, it is moist and after 21 Jun, it is dry.	or XERIC if For 45 consecutive days in all parts SMCS during the 4 mo after 22 Dec, it is moist and after 21 Jun, it is dry.		

1. Soil moisture regimes.[a] Amount of time the SMCS is moist is determined when the soil temperature is greater than 5°C, except where specified.

THE AQUIC SOIL WATER REGIME AND RELATED SOIL WATER REGIMES

The aquic soil water regime is a reducing regime that is virtually free of dissolved O_2 because the soil is saturated by groundwater or by water of the capillary fringe. Some soil horizons may be saturated with water for prolonged periods where dissolved O_2 is present because of a rapid recharge of water in the horizon or because of the environment, which is unfavorable for microorganisms, as can happen when the temperature is below 1°C. These horizons do not have an aquic soil water regime.

The aquic soil water regime is used at the suborder and subgroup level in Soil taxonomy. To be used at the suborder level, the whole soil must be saturated, while for the subgroups only the lower horizons must be saturated. The soil is considered saturated if water stands in an unlined borehole at such a shallow depth that the capillary fringe reaches the soil surface, except in noncapillary pores.

Using the "aquic soil water regime" at the suborder and subgroup level is one way to express different degrees of wetness in the soil. An "aeric" subgroup is provided for in some aquic suborders to express another state or degree of wetness. The following example illustrates this.

Taxa	Category at which wetness is expressed	Degree of wetness
Typic Tropaquult	Suborder	Very wet
Aeric Tropaquult	Subgroup	Moderately wet
Aquic Tropudult	Subgroup	Slightly wet

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DETERMINATION OF CLIMATIC REGIME ACCORDING TO
SOIL TAXONOMY(USDA,1974)
USING FRANKLIN NEWHALL SYSTEM OF COMPUTATION

STATION : CHICHAOUA LATITUDE : 31 33 N

INPUT DATA:	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
PRECIPITATION:	22.9	20.3	25.4	15.2	7.6	5.1	0.3	0.5	7.6	17.8	27.9	22.9
TEMPERATURE :	10.5	12.0	14.2	16.7	20.4	23.0	27.0	27.6	24.7	20.7	14.4	11.3

OUTPUT : CALCULATED EVAPOTRANSPIRATION ACCORDING TO THORNTHWAITE

19.1	24.1	43.4	57.9	94.3	119.8	167.4	163.8	120.6	80.7	35.5	21.7

ANNUAL RAINFALL : 173.5 MM ANNUAL EVAPOTRANSPIRATION : 948.5 MM

SOIL TEMPERATURE REGIME AT 50 CM DEPTH ESTIMATED FROM AIR TEMP.DATA
BY ADDING 2.5C TO ANNUAL MEAN AND REDUCING AMPLITUDE BY A FACTOR 0.66

MEAN SOIL TEMPERATURES (DEGREES CENTIGRADES)		SEASONS WHEN SOIL TEMPERATURE IS HIGHER THAN				
		FIVE DEGREES		EIGHT DEGREES		REGIME
ANNUAL	SUMMER - WINTER DIFF.	BEGIN	LENGTH (DAYS)	BEGIN	LENGTH (DAYS)	
21.1	15.9	14.2	9.6	360	360	THERMIC

MOISTURE CONDITION CALENDER
(1 = DRY 2 = PARTLY DRY 3 = MOIST)

MONTH	DAYS 1.....>11.....>21.....>30
JAN	1111111111 1111111111 1111111111
FEB	1111111111 1111111111 1111111111
MAR	1111111111 1111111111 1111111111
APR	1111111111 1111111111 1111111111
MAY	1111111111 1111111111 1111111111
JUN	1111111111 1111111111 1111111111
JUL	1111111111 1111111111 1111111111
AUG	1111111111 1111111111 1111111111
SEP	1111111111 1111111111 1111111111
OCT	1111111111 1111111111 1111111111
NOV	1111111111 1111111111 1111111111
DEC	1111111111 1111111111 1111111111

NUMBER OF CUMULATIVE DAYS THAT THE MOISTURE CONTROL SECTION IS			HIGHEST NUMBER OF CONSECUTIVE DAYS THAT MCS IS			DRY DURING ONE YEAR	MOIST WHEN SOIL TEMP. IS ABOVE 5 DEG.	MOIST IN SOME PARTS AFTER STICE	MOISTURE REGIME
DRY OR DRY	MOIST OR DRY	MOIST ST	DRY OR DRY	MOIST OR DRY	MOIST ST	IN ONE YEAR	WHEN TEMP > 8	SUMMER SOL- STICE	WINTER SOL- STICE	
360	0	0	360	0	0	0	0	120	0	ARIDIC

2. Soil moisture temperature regime of Chichaoua Station.

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FAKULTEIT WETENSCHAPPEN
REGIONALE BODEMKUNDE

DETERMINATION OF CLIMATIC REGIME ACCORDING TO
SOIL TAXONOMY (USDA, 1974)
USING FRANKLIN NEWHALL SYSTEM OF COMPUTATION

STATION : CASABLANCA LATITUDE : 33 34 N

INPUT DATA:	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
PRECIPITATION:	50.8	48.3	48.3	38.1	20.3	5.1	0.3	0.8	5.1	40.6	66.0	73.7
TEMPERATURE :	10.2	12.7	14.3	15.3	17.6	20.4	22.5	23.1	21.9	19.6	16.1	13.5

OUTPUT : CALCULATED EVAPOTRANSPIRATION ACCORDING TO THORNTHWAITE
21.6 31.2 46.1 59.3 77.2 101.3 122.6 121.2 98.7 76.2 48.7 34.7
ANNUAL RAINFALL : 527.4 MM ANNUAL EVAPOTRANSPIRATION : 837.7 MM

SOIL TEMPERATURE REGIME AT 50 CM DEPTH ESTIMATED FROM AIR TEMP.DATA
BY ADDING 2.5C TO ANNUAL MEAN AND REDUCING AMPLITUDE BY A FACTOR 0.66

MEAN SOIL TEMPERATURES (DEGREES CENTIGRADES)				SEASONS WHEN SOIL TEMPERATURE IS HIGHER THAN FIVE DEGREES		EIGHT DEGREES		REGIME
ANNUAL	SUMMER	WINTER	DIFF-EREN CE	BEGIN	LENGTH (DAYS)	BEGIN	LENGTH (DAYS)	
19.8	22.8	16.5	6.3	360		360		THERMIC

MOISTURE CONDITION CALENDER
(1 = DRY 2 = PARTLY DRY 3 = MOIST)

MONTH	DAYS 1--------11--------21------30
JAN	2222222222 2222233333 3333333333
FEB	3333333333 3333333333 3333333333
MAR	3333333333 3333333333 3333333333
APR	3333333333 3333333333 3333333333
MAY	3333333333 3333333333 3333333333
JUN	3333333333 3222222222 2222222222
JUL	1111111111 1111111111 1111111111
AUG	1111111111 1111111111 1111111111
SEP	1111111111 1111111111 1111111111
OCT	1111111111 1111111111 1111111111
NOV	1111111111 1111122222 2222222222
DEC	2222222222 2222222222 2222222222

NUMBER OF CUMULATIVE DAYS THAT THE MOISTURE CONTROL SECTION IS				HIGHEST NUMBER OF CONSECUTIVE DAYS THAT MCS IS				MOISTURE REGIME
DURING ONE YEAR	WHEN SOIL TEMP. ABOVE 5 DEG.			MOIST IN SOME PARTS		DRY AFTER		
DRY OR MOIST ST	DRY OR MOIST ST	IN ONE YEAR		WHEN TEMP. > 8		MOIST SUMMER SOL- STICE	MOIST WINTER SOL- STICE	
135	79	146	135	79	146	225	225	120	105	XERIC

3. Soil moisture temperature regime of Casablanca Station.

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GEOLOGISCH INSTITUUT

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REGIONALE BODEMKUNDE

DETERMINATION OF CLIMATIC REGIME ACCORDING TO
SOIL TAXONOMY(USDA,1974)
USING FRANKLIN NEWHALL SYSTEM OF COMPUTATION

STATION : SONGKHL51.76 LATITUDE : 7 11 N

INPUT DATA:	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
PRECIPITATION:	125.0	35.8	41.7	61.5	126.9	96.4	110.9	111.9	126.0	309.1	594.8	433.0
TEMPERATURE :	26.3	27.3	27.8	28.5	28.2	27.9	27.6	27.6	27.2	26.8	26.5	26.5

OUTPUT : CALCULATED EVAPOTRANSPIRATION ACCORDING TO THORNTHWAITE

	137.7	129.7	148.0	154.7	156.7	148.0	152.3	150.9	146.9	139.0	133.6	137.7

ANNUAL RAINFALL :2173.1 MM ANNUAL EVAPOTRANSPIRATION :1729.4 MM

SOIL TEMPERATURE REGIME AT 50 CM DEPTH ESTIMATED FROM AIR TEMP.DATA
BY ADDING 2.5C TO ANNUAL MEAN AND REDUCING AMPLITUDE BY A FACTOR 0.66

MEAN SOIL TEMPERATURES (DEGREES CENTIGRADES)			SEASONS WHEN SOIL TEMPERATURE IS HIGHER THAN			
			FIVE DEGREES		EIGHT DEGREES	REGIME
ANNUAL	SUMMER	WINTER	DIF- ERENCE	BEGIN	LENGTH (DAYS)	BEGIN	LENGTH (DAYS)	
29.9	31.1	28.7	1.5		361		360	ISOHYPERTH.

MOISTURE CONDITION CALENDER
(1 = DRY 2 = PARTLY DRY 3 = MOIST)

MONTH	DAYS 1--------->11.......>21.......>3.
JAN	3333333333 3333333333 3333333333
FEB	3333333333 3333333333 3333333333
MAR	3333333222 2222222222 2222222222
APR	2222223221 1111122222 2222111111
MAY	1111111111 1111122222 2222222222
JUN	2222222222 2211122222 2222222222
JUL	2221111111 1111122222 2222222222
AUG	2222222111 1111122222 2222222222
SEP	2222222222 2111122222 2222222222
OCT	2222222222 2222233333 3333333333
NOV	3333333333 3333333333 3333333333
DEC	3333333333 3333333333 3333333333

NUMBER OF CUMULATIVE DAYS THAT THE MOISTURE CONTROL SECTION IS			HIGHEST NUMBER OF CONSECUTIVE DAYS THAT MCS IS			
DURING ONE YEAR	WHEN SOIL TEMP. ABOVE 5 DEG.	MOIST IN SOME PARTS	DRY AFTER SUMMER	MOIST AFTER WINTER	MOISTURE REGIME	
DRY OR MOIST	DRY OR MOIST	IN ONE YEAR	WHEN TEMP > 8	SOL- STICE	SOL- STICE	
53	165	142	53	165	142	204	14	67	USTIC

4. Soil moisture temperature regime of Songkhla Station.

RIJKSUNIVERSITEIT GENT
GEOLOGISCH INSTITUUT

FAKULTEIT WETENSCHAPPEN
REGIONALE BODEMKUNDE

DETERMINATION OF CLIMATIC REGIME ACCORDING TO
SOIL TAXONOMY(USDA,1974)
USING FRANKLIN NEWHALL SYSTEM OF COMPUTATION

STATION : NARATH151.76 LATITUDE : 6 26 N

INPUT DATA:	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
PRECIPITATION:	214.3	56.2	78.8	61.5	148.5	134.9	131.5	146.2	211.6	307.3	633.1	483.3
TEMPERATURE :	26.3	26.9	27.7	28.6	28.4	28.0	27.8	27.6	27.5	27.0	26.3	25.9

OUTPUT : CALCULATED EVAPOTRANSPIRATION ACCORDING TO THORNTHWAITE
127.7 125.5 146.0 154.7 156.7 152.2 152.3 150.9 145.1 143.7 125.8 121.9
ANNUAL RAINFALL :2697.7 MM ANNUAL EVAPOTRANSPIRATION :1704.7 MM

SOIL TEMPERATURE REGIME AT 50 CM DEPTH ESTIMATED FROM AIR TEMP.DATA
BY ADDING 2.5C TO ANNUAL MEAN AND REDUCING AMPLITUDE BY A FACTOR 0.66

MEAN SOIL TEMPERATURES (DEGREES CENTIGRADES)		SEASONS WHEN SOIL TEMPERATURE IS HIGHER THAN			
	DIF-	FIVE DEGREES		EIGHT DEGREES	REGIME
ANNUAL SUMMER WINTER	ERENCE	BEGIN	LENGTH (DAYS)	BEGIN	LENGTH (DAYS)
29.0	3.1	29.1	1.0	34	360	ISOHYPERTH.

MOISTURE CONDITION CALENDER
(1 = DRY 2 = PARTLY DRY 3 = MOIST)

MONTH	DAYS 1--------> 11--------> 21------> 30
JAN	3333333333 3333333333 3333333333
FEB	3333333333 3333333333 3333333333
MAR	3333333333 3333333333 3333333333
APR	3333333333 2222233333 3333222222
MAY	2222222222 2222233333 3333333333
JUN	3333333333 3333333333 3333333333
JUL	3333333333 3333333333 3333333333
AUG	3333333333 3333333333 3333333333
SEP	3333333333 3333333333 3333333333
OCT	3333333333 3333333333 3333333333
NOV	3333333333 3333333333 3333333333
DEC	3333333333 3333333333 3333333333

NUMBER OF CUMULATIVE DAYS THAT THE MOISTURE CONTROL SECTION IS DRY DURING THE YEAR		WHEN SOIL TEMP. IS ABOVE 5 DEG.	HIGHEST NUMBER OF CONSECUTIVE DAYS THAT MCS IS MOIST IN SOME PARTS		MOISTURE REGIME
DRY	MOIST	DRY	MOIST	IN ONE YEAR	WHEN TEMP > 5	SUMMER STICE	WINTER STICE	
OR	OR	OR	OR			SOL-	SOL-	
DRY		DRY						
2	31	329	0	31	329	360	360	0	95	UDIC

5. Soil moisture temperature regime of Narathiwat Station.

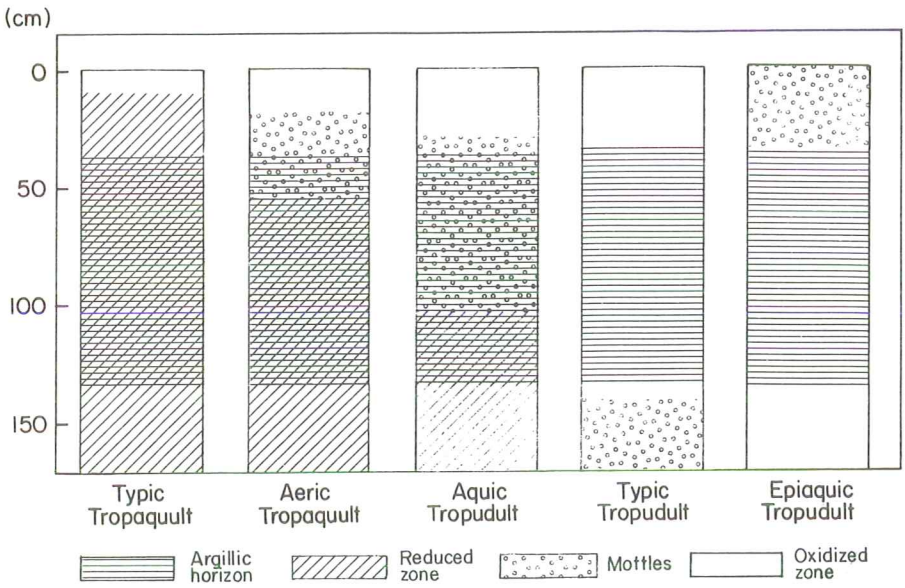
In the above example, the Typic Tropaquult is a very poorly drained soil and the Aeric Tropaquult is a poorly drained soil, while the Aquic Tropudult is a moderately well drained soil -- the Typic Tropudult being the well drained counterpart (Fig. 6). The three or four soils may form a continuum in the landscape.

The aquic subordinate nature is implied in some subgroups even though the definition of the subgroups may not specify it. Examples of this are the pachic and cumulic subgroups used in many taxa of Mollisols and the vertic subgroups in many orders. In these cases the wetness aspect is emphasized in the map unit description as there is no indication of wetness in the family name. Similarly, a "peraquic" condition is provided for but does not appear in any taxon name. Many of the wetlands described in the introduction would have peraquic conditions.

The term "epiaquic" defines a special condition and is used only in some subgroups of the Ultisols and Oxisols. These soils do not

> have in all parts of the soil above a depth of 75 cm, a hue redder than 10YR and a color value, moist, of 4 or more if there are mottles of high chroma within this depth and if the hue becomes redder with a depth within 1 m of the soil surface.

The epiaquic subgroup is provided for soils with a perudic soil moisture regime. The intense wetness during the rainy season causes some reduction of Fe in



6. Schematic diagram to show wetness states in Ultisols.

the upper part of the profile with concomitant downward migration. The upper part of the soil has marks of water stagnation while, at depth, the soil is reddish in color and is well drained. Figure 6 illustrates these concepts using Ultisols as examples.

DEFINITION OF AQUIC AND RELATED CONDITIONS

Soil taxonomy differs from all other classification systems in not considering all wet soils in one class, as for example Sol hydromorphic in the French classification or Gleysols in the FAO/Unesco legend. Profile development or other important properties are considered at the order level, and most orders have an "aqu..." suborder to express hydromorphic conditions.

The definitions of the "aqu" suborders vary, but all carry the general term "has an aquic soil moisture regime or is artificially drained...." The presence of an aquic soil moisture regime by itself is sufficient to place a soil in the "aqu" suborder. If the soil is drained, additional criteria, which differ from order to order, are provided to permit the placement of the soil. The presence of a histic epipedon or sulfuric horizon or sulfidic material at shallow depths is sometimes sufficient to place the soils in the suborder. These qualifying criteria separate those soils that have recently become wet (through irrigation, etc.) and do not have morphological evidence from soils that have developed under aquic conditions and have evidence of moisture saturation.

As in the suborders, the definition for aquic subgroups varies with the great groups. If diagnostic horizons are present, the definition generally requires that the upper part of the horizon have mottles with chroma of 2 or less. In other cases, a saturated condition within 1.5 m suffices. There are some inconsistencies in the system. An example is the Aquic Argixerolls. On p. 311 of Soil taxonomy the definition requires this aquic subgroup to have mottles only if the soil is artificially drained. The description of this subgroup (p. 312) requires it to have mottles even if it is artificially drained. In these cases, the key takes precedence over the description.

In the "aqu" suborders, as in the Typic Tropaquults, the low chroma mottles occupy more than 60% of the volume between the Ap horizon or 25 cm and the 75 cm depth. In the aeric subgroup of these great groups (e.g., Aeric Tropaquult), the mottles are less intense (<60%) or occur deeper in the soil (Fig. 1). The definitions are written to express this concept.

Aquic conditions are handled differently and perhaps inadequately in the Vertisol and Aridisol orders. In the Vertisols aquic conditions are only brought in at the subgroup level when there are distinct or pro-

minent mottles within 50 cm of the soil surface. One basic problem with the Vertisols is that the color of the soil material is dark, making it difficult to see the marks of water stagnation with concomitant difficulties of defining a mutually exclusive class.

As in the Vertisols, only aquic subgroups are provided for in the Aridisols. This is because the Aridisols have an aridic soil moisture regime. There is only one great group, the Salorthids, which is permitted to have and requires water saturation for prolonged periods. In this case, the very high electrical conductivity of the soil solution has effects similar to aridic conditions with respect to plant growth.

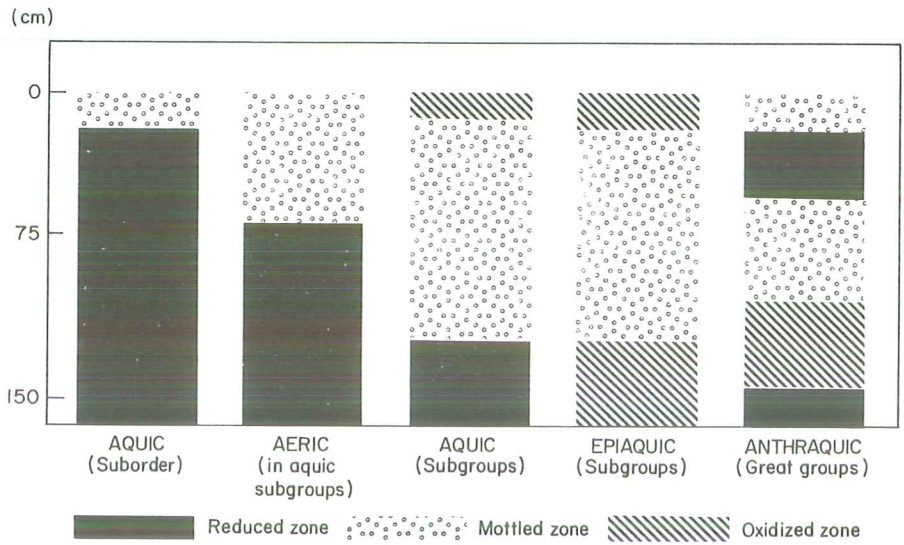
INDUCED WETNESS IN SOILS

Modification of soils for specific purposes is an age-old practice. The induced changes may affect only the surface horizons without many consequences on the taxonomic classification. Other practices, or the cumulative effect of some practices, may result in marked changes that are more permanent. The resulting features could be used as attributes to define taxa. A good example is the deep plowing of some tulip-growing soils in the Netherlands; a special suborder -- Arrents -- has been created for such soils. Other examples of anthropogenic materials are the plaggen and the anthropic epipedon.

These are the only examples in Soil taxonomy where special horizons or taxa have been created to handle anthropogenic influences. Prolonged paddy cultivation on soils that are not naturally wet has been reported to induce permanent changes (2, 3). These changes include reworking of surface materials through terracing, formation of plow pans or traffic pans, and formation of surface gley.

Terracing involves soil removal from the in-slope part and filling-up at the out-slope portion of the slope. The extent of the disturbance depends on the slope and the width of the terraces. Terraces made for perennial crops on steep land may involve a cut to a depth of more than a metre. In Malaysia, terraces for rubber and oil-palm cultivation may be on the C horizon. Classification of such disturbed soils is a problem. Cut-and-fill is a problem to a lesser degree in the preparation of land for rice cultivation. The disturbed part of the profile is generally less than 50 cm and, if important, can be considered as a "disturbed phase" of a taxon.

A more severe pedological change is induced by rice cultivation for prolonged periods on normally nonaquic soils. The formation of a plow pan or a traffic pan is an important morphogenetic property of the soil and could be brought into Soil taxonomy.



7. Schematic diagram to show different states of wetness as employed in Soil Taxonomy (and with new proposal).

Although many observations have been made, there are sufficient studies on a range of such pans to develop a definition for taxonomic purposes.

In paddy soils, puddling and changing the hydraulic conductivity of the surface layers is a management practice that results in a perched water table. The normal profile in such soils consists of an Ap horizon, a deeply reduced layer of 30-50 cm, followed by a yellow to red oxidized zone of the original nonaquic soil. This may be underlain by a permanent water table. Moormann and van Breemen (3) have suggested the term "anthraquic" for this induced feature. An anthraquic horizon may be defined based on the properties of the horizon and specifically in relation to the underlying oxidized layer. The place of such soils in Soil taxonomy needs careful consideration.

These considerations are the subject of discussion by the new International Committee on Aquic Soil Water Regimes (ICOMAQ) appointed by the Soil Management Support Services. Suggestions for consideration by this committee are provided in Appendix 2 and illustrated in Figure 7.

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Appendix 1
Soil Moisture Regimes

ARIDIC or TORRIC -- Usually dry or only occasionally moist. Little or no present leaching; soluble salts accumulate.
1. Dry in all parts >1/2 time, soil temperature >5°C, >5/10 yr; and
2. Never moist in some part for 90 consecutive days, soil temperature >8.3°C, >5/10 yr.

Note: Includes most if not all areas with hyperthermic temperature regimes.

UDIC -- Usually moist. Well-distributed precipitation or enough rainfall in summer such that stored moisture plus rainfall equals or exceeds evapotranspiration.
1. Moist in all parts >3/4 time, >5/10 yr; and
2. Not dry in all parts for 45 consecutive days during the 4 months after 21 Jun, 6/10 yr.

USTIC -- Intermittently moist, effectual summer rainfall. Usually some moisture present during season of maximal evapotranspiration.
1. Moist in some part >1/2 time, soil temperature >5°C; and
2. Not moist in all parts >3/4 time, >5/10 yr; and
3. Not dry in all parts for 45 consecutive days during the 4 mo after 22 Dec, 6/10 yr; and

4. If in areas with isotemperature regime, then only 1 and 2 apply.

Note: Not applied to areas with cryic or pergelic temperature regimes.

XERIC -- Intermittently moist, ineffectual or no summer rainfall. Usually moisture present during season of minimal evapotranspiration and little or no moisture during season of maximal evapotranspiration.

1. Dry in all parts for 45 consecutive days during the 4 mo after 21 Jun, 6/10 yr; and
2. Moist in all parts for 45 consecutive days during the 4 mo after 22 Dec, 6/10 yr; and
3. a. Moist in some part >1/2 time, soil temperature >5°C, or
   b. Moist in some part for 90 consecutive days, soil temperature >8°C, 6/10 yr.

Note: Not applied to areas with isotemperature regimes.

AQUIC -- Reducing regime (much of the time, not necessarily all the time); saturated at least a few days; whole soil for suborders and great groups, lower horizons in subgroups. This is the only regime that does not apply to the soil moisture control section. In this paper, it is referred to as soil water regime.

Appendix 2
Proposals for ICOMAQ

Plow pan or traffic pan

The terms "plow pan" and "traffic pan" are descriptive terms that denote the process of the formation of these pans but are not suitable for taxonomic purposes. They are replaced by the term "dasyk pan" which is derived from the Greek "dasys" meaning compact, and in accordance with the nomenclature in Soil taxonomy. A proposed definition is as follows:

The dasyk pan is a subsurface horizon formed by the physical compaction of soil particles by prolonged shearing and pressure at a constant depth by cultivation implements. The soil particles may or may not be cemented by a secondary accumulation of carbonates or other cements and are characterized by a laminated fabric with Fe and Mn mottles or concretions. These frequently mark the limit of an overlying reduced layer and an underlying oxidized layer, though this by itself is not a differentiating criterion.

A dasyk pan is identified by the following:

- Compaction is strong enough that the bulk density is 1.8 or more and at least 0.2 units higher than the underlying horizon.

- The pan is continuously horizontal, unless broken, and has a fine to medium laminar structure in the dry state.
- The lower part of the pan has Fe and Mn mottles or concretions that occupy at least 10% of the volume of the pan.
- If carbonates are present, the pan must meet requirements 1, 2, and 3 listed above to differentiate it from a calcic horizon (a petrocalcic horizon takes precedence over a dasyk pan). If the pan meets the requirements of a calcic horizon, the term "calci-dasyk" may be used.
- The minimum thickness of the pan is 5 cm.
- If fractured, the average lateral distance between fracture points is 25 cm or more.

Anthraquic horizon

An anthraquic (Gr. anthropikos = related to human beings; L. aqua = water) horizon is a subsurface horizon formed through prolonged puddling and flooding resulting in a reduced layer in the soil. This management practice takes place in both naturally wet and well drained soils and is only significant for classification if it induces permanent features in the soil. Unlike normally wet soils, which are reduced throughout or have an oxidized zone over a reduced zone, soils with an anthraquic horizon have a reduced zone overlying an oxidized or a less reduced zone. The terms "stagnogley" or "inverted gley" have been used to describe such soils.

The anthraquic horizon has the following properties:

- The anthraquic horizon is a subsurface horizon with a reducing regime virtually free of dissolved O_2 for at least 2 mo in a year.
- The horizon is at least 20 cm thick unless it starts at the surface, when it should be at least 30 cm thick. The upper boundary of the horizon is within 50 cm of the soil surface.
- The color of the horizon is blue or grey and the chroma of the soil matrix is 2 or less in at least 60% of the volume of the soil. In addition, the chroma of the matrix of the horizon is at least 2 units lower than the underlying horizon.
- The horizon may incorporate all or part of a dasyk pan.
- The lower boundary of the horizon is distinct in terms of color change and may be marked by the presence of Fe and Mn mottles and concretions.

Placement in Soil taxonomy

In this proposal, the anthraquic horizon and dasyk pan are considered diagnostic features. It is assumed that the dasyk pan is present only in soils with aquic or

anthraquic soil water regimes. The two diagnostic features may be considered to define special taxa as follows:

Alfisols

HAA	Plinthaqualfs
HAB	Natraqualfs
HAC	Duraqualfs
HAD	Dasaqualfs
HAE	Anthraqualfs
HAF	Fragiaqualfs
HAG	Glossaqualfs
HAH	Albaqualfs
HAI	Ubraqualfs
HAJ	Ochraqualfs

(Note: Tropaqualfs are eliminated.)

Inceptisols

IAA	Sulfaquepts
IAB	Placaquepts
IAC	Halaquepts
IAD	Fragiaquepts
IAE	Cryaquepts
IAF	Plinthaquepts
IAG	Dasaquepts
IAH	Anthraquepts
IAJ	Humaquepts
IAK	Haplaquepts

(Note: Andaquepts and Tropaquepts are eliminated.)

Ultisols

FAA	Plinthaquults
FAB	Dasaquult
FAC	Anthraquult
FAD	Fragiaquult
FAE	Albaquult
FAF	Paleaquult
FAG	Ochraquult
FAH	Umbraquult

(Note: Tropaquults are eliminated.)

SOIL TAXONOMY (JOINT)

MAJOR CHARACTERISTICS AND CLASSIFICATION OF WET INCEPTISOLS AND HISTOSOLS

L. MONCHAROEN

This paper reviews the major characteristics and present classification of wet Inceptisols and Histosols. A comparison of soil conditions of some soils in Southeast Asia with the present classification of wet Inceptisols indicates a definite need for improving the definition of cambic horizon in coastal plain areas. At this time, there is very little research on the classification and testing of Histosols according to Soil taxonomy. There is also a very urgent need for further research into the nature and classification of Histosols in intertropical areas.

Histosols and wet Inceptisols are two kinds of soils that are geographically closely related. Both soils occur extensively in river plains, tidal flats, and tundra areas of many places in the world. Apart from the tundra areas, river delta and tidal flat systems can be said to form their physiographic positions. The wetness condition is a necessary state for the formation of most Histosols, and it characterizes some of the Inceptisols.

WET INCEPTISOLS

According to Soil taxonomy (5), wet Inceptisols belong to the suborder Aquepts. Aquepts have a cambic or sulfuric horizon. Their natural drainage is poor or very poor, and if they have not been artificially drained the water table lies close to or at the surface at some time during each year but not during all seasons. These soils are found extensively in various contrasting environments: on the broad, nearly level alluvial and lacustrine plains, in the tundra areas, in the tropics, and in warm regions of the midlatitudes.

The worldwide distribution of wet Inceptisols is shown in Figure 1. From the map, it is readily apparent that these soils are found in all parts of the world and on practically every continent. The most extensively occurring types of Aquepts are the Cryaquepts, which

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1. Distribution of principal Histosols and wet Inceptisols (adapted from Soil Geography Unit, SCS, USDA).

are found mainly in the higher latitudes of North America and Eurasia. These soils are largely under tundra or boreal forest. In the midlatitudes, the predominant types of Aquepts are Haplaquepts, which are restricted to the flat or nearly flat floodplains of the larger rivers (e.g., the Ganges, Mississippi, and Euphrates) and the tidal flats of these areas. For the most part these soils are under cultivation. Tropaquepts are the Aquepts of the world's intertropical regions. Tropaquepts are also usually found on flat alluvial plains associated with the larger rivers (e.g., the Amazon, Nile, Irrawaddi, Chao Phraya, and Mekong) and sometimes on tidally affected areas.

Since a review of all the various kinds of wet Inceptisols would be prohibitively long, this paper will deal instead with the agriculturally more important ones, specifically those found in the tropics. These Aquepts constitute the more important soils for the production of rice; consequently the scope of this paper can be further reduced to include only the rice-growing soils.

The suborder Aquepts, though taxonomically homogeneous, shows a wide range of features when lower categories are considered. Some Aquepts have a placic horizon or duripan, while others may have high salt contents. These characteristics are used to define the lower categories. Table 1 shows some properties of Aquepts that have been reported in the literature. Examples of Aquepts on which rice is grown (10) are Sulfaquepts, Icopaquepts, Haplaquepts, Halaquepts, Andaquepts, and Humaquepts.

Sulfaquepts

A Sulfaquept is an acid sulfate soil with a sulfuric horizon (a horizon that contains jarosite mottles and a pH <3.5) at less than 50-cm depth. Brinkman (4) has estimated the worldwide extent of acid sulfate soils as about 13 million ha with about half (about 6.7 million ha) concentrated in Asia and the Far East, 3.7 million ha in Africa, and another 2.1 million ha in Latin America. The most extensive occurrence of acid sulfate soils in Southeast Asia is in the Chao Phraya and Mekong River deltas (5). Acid sulfate soils indeed occur widely in the lower part of the Chao Phraya Basin, though recent investigations suggest that these soils are not Sulfaquepts but rather sulfic subgroups of Tropaquepts (22, 21). The most extensive areas of Sulfaquepts in Southeast Asia, therefore, are in the Mekong River delta and in the coastal areas of Sumatra and Kalimantan (10).

Table 1. Major characteristics of some Aquepts.

Country	Soil series	Horizon	Depth (cm)	Particle size class (%)			pH		% O.C.	CEC (meq/ 100 g)	Ca (meq/ 100 g)	Mg (meq/ 100 g)	K (meq/ 100 g)	Na (meq/ 100 g)	Base saturation (%)	$CaCO_3$ (%)
				Sand	Silt	Clay	H_2O	KCl								
Korea	Jeonbug	Ap_{1g}	0-10	11	71	18	4.6	–	1.22	8.2	2.3	2.1	0.1	0.4	59	30
		Ap_{2g}	10-19	2	80	18	4.7	–	0.81	8.8	2.7	2.8	0.1	0.5	68	33
Haplaquepts		B_{21g}	19-27	9	70	21	6.1	–	0.35	9.0	3.5	4.4	0.1	0.6	95	43
(Yong Hwa Shin 1978)		B_{22g}	27-44	6	65	29	6.5	–	0.17	12.6	4.9	6.4	0.2	0.9	97	63
		B_{23g}	44-85	2	71	27	6.5	–	0.12	15.8	4.8	9.8	0.2	1.4	102	10
		B_{3g}	85-120	4	69	27	6.7	–	0.12	16.0	4.5	10.5	0.4	1.5	106	168
		C_{1g}	120-160	5	73	22	6.6	–	0.35	14.5	3.8	9.5	0.5	1.4	104	227
Malaysia	Sedu	O	6-0	–	–	–	4.5	3.9	36.8	–	–	–	–	–	–	–
Typic Tropaquepts		A_1	0-6	17.1	36.4	46.5	4.3	3.4	12.4	–	1.31	0.64	0.16	0.04	3.82	–
(Paramananthan, pers.		B_{21g}[a]	6-32	4.0	40.2	55.8	3.5	3.1	6.1	–	0.32	0.26	0.14	0.18	1.85	–
comm.)		B_{22g}[a]	32-60	0.1	45.6	54.3	3.4	3.0	3.2	52.12	0.21	0.61	0.19	0.11	3.08	–
		B_{3g}[a]	60-85	3.2	44.3	52.3	3.4	3.1	3.8	51.98	0.38	3.84	0.24	0.52	12.51	–
		C_G	85	4.6	36.8	58.6	3.1	2.8	6.1	68.64	0.41	6.91	0.43	1.69	20.66	–
	Bernam	A_1	0-14	9.2	20.6	70.3	4.4	4.2	2.44	33.20	0.39	12.73	0.83	1.17	64.07	–
Typic Sulfaquepts		B_{21G}	14-40	4.7	32.6	62.7	4.5	4.2	0.63	43.65	2.37	20.95	0.35	1.10	97.14	–
(Paramananthan, pers.		B_{22G}	40-60	5.3	35.8	58.3	4.6	4.3	0.50	53.11	2.60	23.96	0.50	1.17	115.04	–
comm.)		B_{CG}	60-100	14.8	38.5	46.8	4.0	3.8	0.60	39.04	2.27	18.89	0.46	1.82	103.81	–
		C_G	100-250	20.3	47.8	31.9	2.9	2.7	1.32	59.25	2.31	14.95	0.21	2.18	89.24	–
Thailand	Rangsit	Ap_g	0-10	10.8	22.2	67.0	3.65	3.45	0.99	27.1	3.10	5.70	0.20	1.90	24	1.00
	(Rs)	A_{2g}	23-31	52.8	19.7	27.5	3.75	3.50	0.30	8.3	1.10	1.90	0.10	0.70	27	0.72
Sulfic Tropaquepts		B_{1g}	31-42	12.4	26.6	61.0	3.75	3.30	0.44	21.3	2.00	4.40	0.20	1.00	24	0.72
(Soil Survey Division,		B_{21g}[a]	42-57	10.0	27.0	63.0	3.55	3.25	0.30	22.3	2.20	4.50	0.20	1.10	23	0.86
Thailand)		B_{22g}[a]	57-87	4.9	27.6	67.5	3.50	3.10	0.27	24.5	2.30	4.90	0.30	1.10	24	0.72
		B_{31g}	86-127	2.3	23.7	74.0	3.45	3.05	0.44	27.2	2.60	5.70	0.50	1.30	27	0.86
		B_{32g}	127-160	3.3	37.7	59.0	3.05	2.75	1.60	28.5	3.10	7.50	0.30	1.50	20	0.00
		C_g	160-200	11.0	21.9	67.1	3.00	2.70	1.81	30.0	5.90	5.60	0.30	1.90	24	0.14
		C	200-300	16.7	25.9	57.4	2.95	2.60	7.20	40.2	11.70	18.10	0.20	3.90	39	0.14

Bangkok (Bk) Typic Tropaquepts (Soil Survey Division, Thailand)	Ap	0-12	1.8	23.7	74.5	5.30	4.10	1.06	28.1	6.90	12.90	1.00	2.90	61	0.44
	A_{12}	12-30	1.0	24.5	74.5	5.85	5.25	0.54	28.9	7.40	13.10	1.10	3.70	73	1.03
	AB_{1g}	30-48	1.6	22.4	76.5	6.50	5.85	0.22	29.4	7.40	13.10	1.10	4.80	80	0.73
	B_{21g}	48-90	1.5	26.0	72.5	6.80	6.10	0.16	30.3	8.00	15.70	1.20	5.80	84	0.73
	B_{22g}	90-120	16.0	24.9	73.5	6.95	6.50	0.20	32.0	9.70	15.80	1.30	7.90	85	0.15
	B_{3g}	130-140	0.5	31.8	67.0	6.95	6.70	0.68	28.8	8.00	17.40	1.80	9.60	87	3.97
	C_{1g}	140-200	1.2	29.1	69.5	7.70	7.30	1.33	30.3	19.10	19.30	2.00	12.20	88	5.88
Bangkhen (Bn) Typic Tropaquepts (Soil Survey Division, Thailand)	Ap	0-15	4.0	45.0	51.0	4.70	4.30	0.77	32.4	33.20	9.40	0.50	2.20	78	1.50
	A_{12g}	15-36	5.0	52.5	42.5	4.40	3.90	0.51	32.4	66.70	11.00	0.40	3.80	85	0.30
	B_{21g}	36-68	8.0	42.0	50.0	4.20	3.50	0.32	25.4	10.40	10.60	0.40	4.00	71	1.05
	B_{22g}	68-88	10.0	30.0	60.0	4.30	4.00	0.41	24.7	8.90	10.10	0.40	3.80	66	0.90
	B_{23g}	88-126	13.5	31.5	55.0	4.15	3.80	0.43	24.5	9.10	9.10	0.40	3.40	62	0.90
	B_{3g}	126-160	7.0	40.5	52.5	4.40	4.00	0.41	23.8	9.50	10.50	0.50	3.90	70	0.90
	C_{1g}	160-210	5.0	45.0	50.0	5.40	5.00	0.60	24.7	10.30	11.70	0.50	4.80	77	1.05
	C_{2g}	210-240	21.0	55.5	23.5	3.15	3.10	1.14	27.3	15.20	15.50	0.50	5.00	62	1.35
Ongkharak (Ok) Sulfic Tropaquepts (Soil Survey Division, Thailand)	Ap	0-14	1.2	43.3	55.5	3.9	3.2	1.29	19.49	4.36	5.05	0.94	1.90	62.85	–
	B_{1g}	14-30	4.3	33.0	62.7	3.6	3.0	0.49	20.69	4.36	5.86	0.58	1.84	61.09	–
	B_{21g}[a]	30-60	3.1	29.4	67.5	3.5	3.0	0.33	22.22	4.39	7.43	0.66	3.00	69.67	–
	B_{22g}[a]	60-115	2.5	27.3	70.2	3.4	2.9	0.16	22.55	4.73	8.97	0.76	1.00	58.56	–
	B_{3g}[a]	115-165	1.5	29.3	74.6	3.5	3.0	1.03	25.77	4.83	10.11	0.92	2.00	69.34	–
	C_{1g}	165-195	1.4	28.4	70.2	3.5	3.1	3.42	28.01	5.26	11.82	0.08	3.00	74.83	–
		195-315	0.6	19.7	79.7	4.0	3.6	3.02	27.68	9.90	24.52	1.48	7.00	100.00	–
	C_{2g}	315-335	1.2	32.8	66.0	4.1	3.6	4.16	29.87	10.22	24.01	1.52	7.00	100.00	–
		335-360	1.5	27.1	71.4	5.1	4.7	2.62	28.50	11.22	23.10	1.59	8.00	100.00	–
Udon (Ud) Aeric Halaquepts (Soil Survey Division, Thailand)	Ap_{1g}	0-12	57.0	36.5	6.5	5.4	4.9	0.37	3.1	2.2	0.8	0.1	6.2	300	0
	Ap_{2g}	12-30	52.0	41.5	6.5	6.7	5.5	0.05	2.9	1.4	0.5	0.04	1.9	131	0
	B_{21tg}	30-60	42.5	38.0	19.5	7.3	6.1	0.18	11.6	4.4	2.2	0.1	6.3	112	0.92
	B_{22tg}	60-90	58.5	26.5	15.0	7.5	6.4	0.41	9.8	3.7	2.0	0.1	6.4	125	0.62
	C_{1g}	90-105	67.0	6.0	27.0	7.7	6.6	0.27	7.7	3.0	1.6	0.1	5.9	138	0.62
	C_{2g}	105-120	57.0	25.0	18.0	7.6	6.7	0.21	11.6	3.8	2.3	0.2	8.0	123	0.31
	C_{3g}	120-150	64.0	21.0	15.0	7.7	6.7	0.03	3.9	3.1	1.8	0.1	7.2	137	0.62

[a] Presence of jarosite mottled.

Icopaquepts

Icopaquepts are the Aquepts of the tropical regions that are in continuously warm areas where the soil temperature at 50-cm depth varies by less than 5°C between summer and winter. They are the most important rice-growing soils in the major and minor alluvial valleys and coastal plains of Asia. Tropaquepts are the dominant soils of the Tamil Nadu region in India (10). In Malaysia, Paramananthan (13) reported that Tropaquepts occur on riverine and marine deposits. About 200,000 ha are found in subrecent deposits in Indonesia and as component soils in alluvial soils that cover an area of about 29,000 km^2 (19). In the Philippines these soils occur on alluvial toeslopes of narrow coastal plains and small river valleys (17). In Thailand, the majority are found in the coastal areas of the Chao Phraya and to a lesser extent on its floodplain (23).

Tropaquepts display a wide range of characteristics. The Tropaquept great group contains subgroups that are transitional to Sulfaquepts (sulfic subgroup). The soils are included in the general category of acid sulfate soils. The vertic subgroup (transitional to Vertisols) has been reported in the Philippines and Thailand.

Haplaquepts

These Aquepts occur in the zone where soil temperatures at 50-cm depth vary by more than 5°C between summer and winter. In Asia, the boundary between the morphologically similar Tropaquepts and Haplaquepts is roughly the 17th parallel (10). On the Indian subcontinent, these soils are found in the West Bengal and northeastern regions and in Bangladesh (3, 11). Haplaquepts are also found in valleys in the northern, nontropical part of Thailand (10).

Haplaquepts are therefore the predominant wet Inceptisol in areas with a distinctly cooler winter climate, e.g., Japan (9), Korea (18), and China (10).

Halaquepts

The Halaquepts are Aquepts that are saline in the upper parts of the profile. With paddy cultivation, the salts may be leached from the soil surface during the growing season, but during the dry season they may accumulate at the surface. Some of these soils correspond to the gleyic Solonchaks of the FAO/UNESCO system. These soils are usually associated with the coastal areas of Vietnam, peninsular Malaysia, Irian Jaya, and Aru, in contrast to Thailand, where the most extensive occurrence of Halaquepts is in the northeast on terraces and floodplains in areas underlain by salt-bearing bedrock (Thailand, Department of Land Development, unpublished soil survey data).

Andaquepts

These soils have developed on pyroclastic material. Such soils have an exchange complex dominated by amorphous materials and low bulk density. Andaquepts are found in volcanic terrains, usually on footslopes and in valleys. They occur most extensively in Japan and less extensively in tropical areas with active vulcanism, especially in the Philippines and Indonesia.

Humaquepts

These soils are nearly black or peaty, very wet acid Aquepts of the midlatitudes. They correspond to the humic gleysols of the FAO/UNESCO system. In Southeast Asia, they occur most extensively along the coastal areas of Java, Kalimantan, Sarawak, Sabah, and Thailand.

Problems in the classification of wet Inceptisols

Most Inceptisols require, by definition, a cambic horizon. Application of the definition of the cambic horizon to the wet soils presents problems, as one of the requirements of the definition (20) is:

> a regular decrease in the amount of organic carbon with depth and a content <0.2% organic carbon at a depth of 1.25 meters below the surface.

During soil survey investigation activities in Thailand and Malaysia, it has been noted that, despite a regular decrease, the amount of organic C remains consistently above 0.2%. This is specifically true for soils that are acid and, as suggested by Kawaguchi and Kyuma (8), the high acidity may retard the decomposition of the organic matter. If the requirement for the cambic horizon is strictly adhered to, then these soils lack a cambic horizon and therefore must be classified as Entisols.

Another situation exists in these soils under acid marine conditions. Soil formation has advanced to form a subsurface horizon that has all the properties of a cambic horizon. However, because of the wetness conditions, the rate of organic matter decomposition is reduced and the irregular distribution of organic C with depth of the original sediment is retained. As a result of this irregular distribution, the soils cannot have a cambic horizon and are forced into Entisols. The soils' other attributes, structure, and color, and the geomorphic position of the soils clearly indicate that soil formation has taken place, and pedogenetically they are more advanced than the Entisols. These soils also have a land use different from that of the adjoining Entisols.

There is an urgent need to improve the definition of the cambic horizon. An unpublished report of Dr. Guy

Smith (1978) attempted to do this, but initial testing of his proposal resulted in unsatisfactory groupings.

An alternative is to permit the irregular distribution of the organic C content (a fluventic feature) in cambic horizons as long as the other properties or requirements are met.

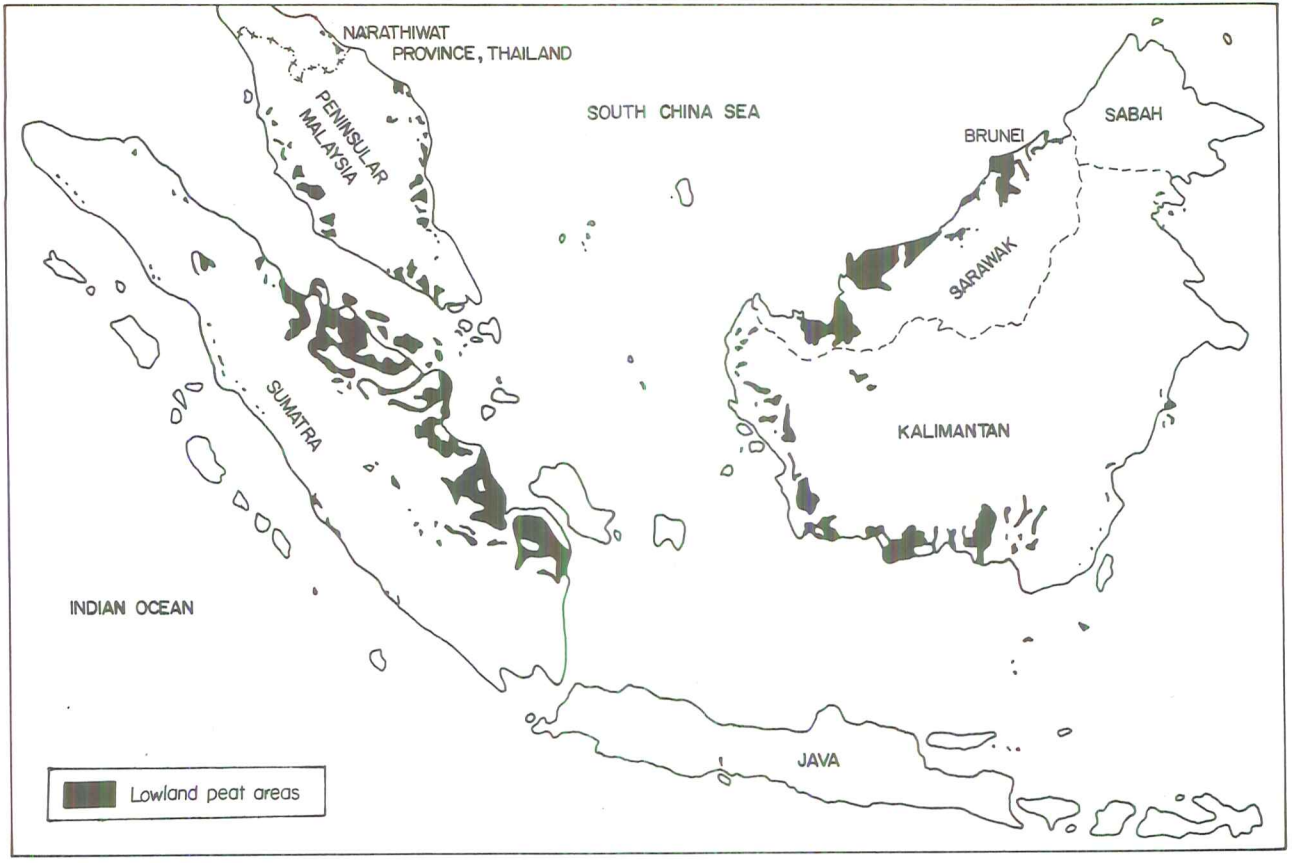
There is a large group of soils that do not have a proper place in Soil taxonomy. These are soils that, because of continuous ponding or other techniques, have developed aquic characteristics. Several terms for this type of soil have been proposed: Aquirozems (80), Hydragric soils (24), and Anthraquic conditions (10). The induced wetness conditions may be sufficiently well expressed for the soil to be classified as an Aquept or belonging to an aquic subgroup; however, the anthropogenic cause of the wetness must be indicated in the classification, perhaps by the use of Anthraquic subgroups. Because these soils do not have the same chemistry as the other wet Inceptisols, they deserve to be recognized separately.

A third problem area deals with the acid sulfate soils as a whole. At a recent conference in Bangkok (1981), the subject was extensively debated. Many different kinds of acid sulfate soils were recognized and suggestions were made to recognize new subgroups (14).

HISTOSOLS

Histosols can form in virtually any climate, even in arid regions, as long as sufficient water is available. In the higher latitudes, Histosols are underlain by permafrost. In contrast, these soils are also found in equatorial regions mainly overlying mineral soils. Histosols are also found in diverse geographic locations like closed depressions, coastal marshes, or steep slopes where there is seepage. The common feature is water. Research data on Histosols outside the temperate regions are for the most part minimal. What follows is a review of the available data, along with comments on some aspects of the classification of Histosols.

Figure 1 shows the worldwide distribution of Histosols, Figure 2 the Southeast Asian occurrences. The major areas of Histosols in Southeast Asia are the high-rainfall equatorial parts of East and West Malaysia, the islands of Sumatra and Kalimantan, and West Irian. Histosols are found to a lesser extent in Thailand, the Mekong Delta, and the Ganges Delta. Elsewhere, they are confined to small inland swamps. It has been estimated that peat soils cover an area of approximately 23.5 million ha in Southeast Asia and the Far East (4). In Southeast Asia, about 16 million ha of Histosols are on Kalimantan and Sumatra, 0.8 million ha in West Malaysia, 1.4 million ha in East Malaysia,



2. Location of major peat swamps in Southeast Asia (2, 23).

10,000 ha on Brunei (2), and 80,800 ha in Thailand (12).

An early attempt at classifying peat soils (16) delineated two broad types of peat:

- ombrogeneous -- organic soils low in nutrients, with low pH, low mineral matter content, and vegetation dependent upon rainwater; and
- topogeneous -- organic soils moderate to high in nutrient status, eutrophic, and having a pH close to neutral.

This classification system was intended primarily for temperate regions. As is usual, when transferring a classification system based on temperate conditions to the tropics, some problems arose. For example, Anderson (1) indicated that peats in Sarawak are partly ombrogeneous and partly topogeneous. Additionally, pollen analysis of a peat deposit in peninsular Thailand indicates it was initially topogeneous before becoming ombrogeneous (7). As Andriesse (2) noted, this system is not applicable to Southeast Asia. The persistence of these terms in some national classification systems, although more restricted in meaning (based upon depth, for example), may still result in some confusion.

Most modern systems of soil classification try to divorce classification from the genetic or topographic point of view. Instead only the soils' physical and chemical characteristics at the time of survey are considered. In many ways this has shown to be a good idea, though it has tended to make some soil taxonomists view soil as an entity separate from the surrounding environment. Changing land use patterns will also affect the soil's classification.

A practical use classification system (for agricultural and reclamation potential) was proposed by Andreisse (2) based upon

- associated vegetation (physical composition),
- chemical composition,
- physiography, and
- nature of underlying material.

This system has some drawbacks in that the present vegetation may not be the vegetation under which the peat formed. For deeper peat soils (>2 m), it becomes a practical surveying problem to ascertain the subsoil type, as most surveys are concerned only with the upper 2 m at most.

Farnham and Finney (6) reviewed many classification systems and the properties of peat soils to form a system comparable to the USDA 7th Approximation. They chose the following criteria.

- thickness of the organic horizon,
- presence or absence of diagnostic horizons and kinds of subsurface horizons, and
- composition and texture.

Histosols are soils composed predominantly of organic matter and are commonly known as peat and muck. By definition more than half of the upper 80 cm of the profile should be organic soil material. Organic soil material has 18% or more organic C if the mineral fraction is 60% or more clay. The definition and classification of Histosols are considered provisional. The suborders based on state of decomposition are: Fibrists, the least decomposed (one is able to recognize two-thirds of the material as being parts of plants); Hemists, intermediate decay; and Saprists (muck soils), the most decomposed. This great group classification is based on temperature regimes and the presence or absence of sulfuric or sulfidic material in the subsoil. Further subdivisions (families, etc.) are distinguished in the USDA taxonomy.

Reclamation and subsequent drainage will also affect the suborder classification by causing the rapid decomposition of a previously well-preserved peat.

As with most other soils, organic soils have also been the subject of various national classification schemes. The nature of Histosols has thus produced a bewildering array of such classifications, most of which have no extranational applications. Indeed, some countries have three classification systems for Histosols within the country (15).

More research into the classification of Histosols is urgently needed. Studies on the classification of Histosols in Thailand are rare. Additionally, there is insufficient testing of classification according to Soil taxonomy. Therefore not much can be said about the problems concerning the classification of Histosols.

Thailand's attempts to reclaim a peat deposit in Narathiwat Province may serve as a case in point. Drainage to control flooding on this soil caused

- annual fire on the peat surface, which reduced the thickness of the organic layer, and
- oxidation of the underlying mineral soil, a brackish water clay, to mottled jarosite.

This would result in a great change in the classification of the soil.

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HYDROMORPHIC VERTISOLS

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The present criteria used by Soil taxonomy to separate poorly drained from better drained Vertisols have proven to be unsuccessful in many places. Considering its genetic as well as its interpretative value, a review is made of how hydromorphic Vertisols could be defined, their occurrence, the reason why Soil taxonomy does not recognize an aquic regime in these soils, and the main problems encountered in its recognition. Water movement along cracks precludes the existence of a moisture control section. The present operational definition of an aquic regime based on an unlined borehole precludes an aquic regime in hydromorphic Vertisols. A review of the literature points out that the lack of a moisture control section looks correct, but for the operational definition of an aquic regime the use of a piezometer or a tensiometer appears to be a solution. Three pedogenetic processes of hydromorphic Vertisols -- oxidation-reduction, organic matter accumulation, and textural differentiation -- are analyzed. The present proposal of the International Committee on Vertisols, ICOMERT, regarding the definition of an aquic regime in Vertisols, that of a suborder Aquert and of Dystraquerts, Planaquerts, and Eutraquerts as great groups, is presented. Research on monitoring water saturation and physical-chemical changes in hydromorphic Vertisols is suggested.

According to Soil taxonomy (41) the order Vertisols includes soils rich in expansive clays with wide and deep cracks up to the surface and with some morphological features that denote the strong shrinking and swelling phenomena to which they have long been subjected. Is it possible to speak of hydromorphic Vertisols? If it is, what general characteristics should they have?

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Considering the foregoing definition, we could say that hydromorphic Vertisols should have prolonged periods of water saturation and of O_2 deficiency. However, they should also have dry periods so that deep and wide cracks can develop. If we want these Vertisols to be separated in Soil taxonomy and to be consistent with hydromorphic soils in other orders, wetness should leave a mark somewhere in the upper 2 m -- if at a high taxonomic level (suborder), at least in the upper solum, and if at a lower level (subgroup), only in the lower solum.

The most consistent mark of hydromorphism left in the soil and used until now is the low chroma colors. But for wetness to affect the color, it is implied that a reduction stronger than that of O_2 consumption should be reached, i.e., at least the Mn^{2+} or Fe^{2+} stage, or both. This also means that wetness should occur when biological activity can take place, i.e., when temperatures are above 5°C and when Mn or Fe, or both Mn and Fe, and sufficient organic matter are present (33, 41).

The duration of water saturation with reduced conditions varies with the mentioned factors, but there are not enough quantified data to establish definite durations under specified circumstances. This situation is not exclusive to hydromorphic Vertisols but is common to all other orders.

DO HYDROMORPHIC VERTISOLS OCCUR?

Have Vertisols that may be considered hydromorphic been found and reported previously? Probably the best and easiest way of finding this out is to look at classification systems and at some comprehensive reviews of Vertisols or similar soils with different nomenclatures. Apparently, only the French System (16) separates Vertisols "without external drainage or hydromorphic," from the ones with external drainage. Both Soil taxonomy (41) and the FAO nomenclature (21) have a subdivision according to color (Pell and Chrom) that implies different drainage conditions but is not exclusive to it; consequently, we cannot be sure from the names whether we are talking about hydromorphic Vertisols or not. But an earlier version of Soil taxonomy, the 7th approximation (40), considered Vertisols with periodic wetness -- the Aquerts -- and as it was used for some time there are reports of Aquerts in certain parts of the world. One example is the review of major soils in Southeast Asia (19), where Aquerts were reported to occur in most countries. Dudal (17), in his comprehensive review of the dark clay soils of tropical and subtropical regions, also reported the occurrence

of poorly drained ones in level or depressed topographies of countries like South Africa, Morocco, Argentina, and India.

In Australia (25), the classification systems do not specifically separate a hydromorphic variety, but in the moister regions features of hydromorphism such as mottling and Mn concretions are found in the black earths. Blokhuis (4), in describing the evolutionary sequences of Vertisols, mentioned that in high rainfall or long-flooding areas of Western and Southeastern Europe there are degraded Vertisols or Vertisol-like soils such as the "Pelosol" of the German (30) and French (16) systems, as well as "smol(el)nitzas" in Eastern European countries, which differ essentially by having more hydromorphic features and increasing clay with depth superimposed on the Vertisol features.

Comerma et al (15) reported that a large percentage of Vertisols in Venezuela that occur in flat or concave backswamp riverine deposits are subject to long periods of ponding. In these conditions hydromorphic features are developed. In the Soviet Union (24) a superaqual series of soil formation occurs within the family of compact soils (including Vertisols) in tropical, subtropical, and temperate belts, forming hydromorphic compact soils (gleyed smolnitzas, gleyed tirses, etc). Finally, through the International Committee on Vertisols, ICOMERT (27), the author has received many personal communications about the presence of poorly drained Vertisols in such places as South Sudan, Israel, Uruguay, Australia, Colombia, and the Southern U.S.

WHY DOES SOIL TAXONOMY NOT HAVE A CLASS OF HYDROMORPHIC VERTISOLS?

Why does Soil taxonomy not consider an aquic moisture regime in Vertisols when it accepted similar processes in the 7th approximation? According to G. Smith (pers. comm.), and partly implied in the chapters on Vertisols and moisture regimes in Soil taxonomy (41), there was no operational definition in the 7th approximation for an aquic moisture regime. Later on, an operational definition was presented in Soil taxonomy. It was based on several premises, as follows:

- The soil is moistened from above and a uniform vertical water front is assumed. This is implied by the existence of a moisture control section and of a moisture regime based on the number of moist or dry days this section has throughout the year. But Vertisols are excluded, as it is considered that the wetting front will be downward, lateral, and upward because of water running into the open cracks. Consequently,

Vertisols are considered not to have a moisture control section, and the moisture regime is defined on the basis of number of days the cracks are open or closed throughout the year.

- An aquic moisture regime is operationally defined as one that is water saturated up to the soil surface (for suborders) for prolonged periods and is observed by using the unlined borehole method. Because of the vertical and oblique cracks or preferential pathways for water in Vertisols, it was considered that the borehole method does not operate well, as water passing through cracks could produce a false water table that does not exist in the surrounding soil matrix of the borehole; in other words, the soil might not be saturated but a water level would be present in the hole at that level.

In short, with the present operational definition of an aquic moisture regime in Soil taxonomy, the existence of one in Vertisols cannot be proven or disproven. The alternative selected was to eliminate Aquerts and to try to separate the better drained from the less better drained Vertisols at the great group level by distinguishing in the upper 30 cm of the soil color chromas equal to or higher than 1.5 (Chrom) or lower than 1.5 (Pell).

Has the separation of Vertisols according to drainage conditions worked well? Comerma et al (15) showed that for Venezuelan Vertisols, Pell grouped the poorly drained ones quite well, but within the population of Chrom, only half were better drained; the other half belonged with Pell with respect to drainage class. The author's personal observations on Vertisols of the Blackland Prairies of Texas have indicated that most Vertisols occur in the Pell class whether they are well or poorly drained. Through ICOMERT I have received many opinions about the improper grouping of soils by Pell and Chrom criteria in many countries. Consequently a revision of the considerations used to exclude an aquic moisture regime from Vertisols is appropriate. The objective is to analyze whether, in view of recent findings, we can find a better way of characterizing, defining, and separating the poorly drained from the better drained Vertisols.

WATER MOVEMENT IN VERTISOLS OR VERTISOL-LIKE SOILS

In this section I am including together with Vertisols other soils that are rich in clay and that develop cracks during the dry season, as they seem to have

similar problems with respect to water entry and movement and the definition of an aquic moisture regime.

Infiltration when cracks are open

It is evident from a review of the literature that these soils behave differently from others with respect to the initial water infiltration, if we start with the cracks open (37); that is, under flooding, irrigation, or heavy rains a large part of the total infiltration occurs in the early period. For example, Yule (42) cited a case in Queensland where 80% of the first 5-hour infiltration occurred in the first 20-30 minutes. Quirk and Blackmore (34) reported that in the Riverine in Australia about 70% of total intake during 4 hours infiltrated the soil in the first 10 minutes. In a Vertic Haplaquept of Louisiana (2), half of the total irrigation applied went down the cracks in about 90 seconds.

The explanation given is that when the volume of incoming water exceeds the infiltration capacity of the areas between the open cracks, a runoff will fall into the cracks. The cracks can initially have such a high volume that, as El Albedine and Robinson (20) mentioned, they can account for 860 m^3/ha or an equivalent of 86 mm of water. Also, as Bouma and Wosten (11) have proved, the absorption surface area of the upper soil surface can be as low as 10% of the surface area of the cracks. So initially the cracks present a much larger surface of infiltration than the upper surface. Consequently, for a period this is quite an important and particular feature of these soils. But does this process continue operating for a long period so that it constitutes a determining factor through time? Bouma and Wosten (11), in their characterization of ponded infiltration into dry cracked clay soils, mentioned that after the soil surface and, consequently, the cracks were covered with water, it took only about 2 minutes for swelling to begin. Also, Allen and Braud (2), in their infiltration study with a Vertic Haplaquept, found that it took only about 60 minutes in the field for the cracks to appear closed, although they were filled with soft mud.

Consequently, the process of water infiltrating through the cracks (horizontally and vertically upward) may be quite important at the beginning but does not remain so for long periods. However, if rains are gentle and the upper soil has more self-mulching or smaller peds, most of the infiltration will be handled by the upper soil, while if rain or flooding is more intense, infiltration through cracks can be more important (7, 28).

Infiltration when cracks close

The preceding considerations applied to the case of Vertisols that occur in climatic or hydrologic conditions that produce several moistening and drying cycles throughout the year, implying several cycles of closing and opening of cracks, would justify the absence of a moisture control section in these soils. But in a condition where rains are concentrated or ponding occurs -- that is, when the soil cracks are moistened, are closed, and do not open again until the following dry season -- these soils might be considered more like other clay soils with low infiltration and low hydraulic conductivity values.

In this respect, there are conflicting opinions and not many measurements. From many articles (3, 6, 10) it is quite evident that after these soils start to moisten swelling occurs and pore size distribution evolves rather quickly. The main process in this respect is reduction of the large macrovoids occurring between aggregates into smaller ones. Nevertheless, under saturated conditions only a small percentage of pores conducted water, and those pores corresponded to a few large planar voids that occurred between structural units. As time went by, these soils, saturated with water or ponded, or both, continued to swell for some time, affecting infiltration. Talsma and Lelij (39) conducted long-term infiltration studies in some Vertisols of Australia and showed that, even after the cracks had closed, infiltration was relatively high (2-3 mm/day), and up to about 8 days the cumulative curve was linear, suggesting an irregular wetting front; but after that a decreasing trend was established, reaching a minimum at about 60 days. Continued swelling is probably the explanation for the decrease, but these few planar voids, related to slickensides, probably continued being the most important pathway for water movement. Even though the general processes are understood, the complication of a changing bulk density with changes in moisture and in pore size distribution and, consequently, in hydraulic conductivity among swelling clays (10, 22) has not allowed a good application of Darcy's law, nor has a complete explanation been developed for water movement in soils with these characteristics.

Another important aspect of water movement in these soils is whether the water front saturates and remains in the upper horizons or whether it reaches the subsoil in the long run. This subject is also controversial and without much data. Moormann and van Breemen (29) and Phillis (32) mentioned Vertisols under rice, which are saturated in the topsoil but dry below. Just how much puddling could reduce percolation to the subsoil is not stated, but it is not mentioned as an important factor. Actual measurements for a long period

are rather scarce. Swartz (38), studying water entry into a black earth under flooding, concluded that as flooding increases in duration, the wetting front gets deeper, but major changes cease at about 3 weeks. Talsma and Lelij (40), also studying ponded black earths, found that with time the full depth (about 3 m) increased in moisture up to about 65 days, but the increase was much larger in the upper 50 cm, although tensiometer readings showed positive (saturation) values for a longer time at 75 cm than at 50- and 30-cm depths. A kind of transient water table was developed in the above soils according to these authors, which would conform more to the hydromorphic processes in pseudogleys (36), but Soil taxonomy does not separate processes of gleys from pseudogleys and stagnogleys. Beside the aquic moisture regime only the epiaquic is used, and it is ascribed to soils with mild reduction in the upper soil, not enough to produce mottles of low chromas.

More data are thus needed to give a better answer to the problem of how deep water saturation may reach in these soils and the factors that may influence them.

Some factors affecting water movement

The above considerations concerning water infiltration and movement under saturated conditions in Vertisols and similar soils are difficult to generalize, as many factors can alter them. The following are among the most important:

- Types of primary and secondary structure in the topsoil as well as in the subsoils are significant. Bouma and Dekker (7) and Bouma et al (8) have proven the differential influence of prisms and angular and subangular blocks on water movement in saturated and unsaturated conditions. The inclination of cracks or slickensides common in Vertisols versus the vertical cracks more common in other cracking soils has not been explored but could play an important role in water penetration into the subsoil.
- The rain or flooding intensity and volume, also mentioned by Bouma and Dekker (7) as well as Johnston and Hill (28), affect the proportion of water infiltrated via the cracks, the cycles of opening and closing of cracks, and the possibility of saturation and ponding.
- The presence of Na and salts affects structural conditions and consequently hydraulic conductivity. Naghshineh-Pour et al (31), analyzing various Vertisols, presented the rather common view that a Na saturation percentage above 10, in other cases near 20, significantly affects hydraulic conductivity, but when high contents of

soluble salts (around 50 meq/litre) are present, its effect is not evident, and with high carbonates it is reduced.

Measuring water tables in swelling soils

As mentioned before, one of the major problems in establishing an aquic moisture regime in Vertisols, and indeed in Vertic subgroups of other orders of Soil taxonomy, is that the present operational definition using the unlined borehole method is uncertain in the case of these soils. This subject was indirectly addressed by Ritchie et al (35) when comparing hydraulic conductivity measurements in swelling clay soils using cores versus field methods. They pointed out that field measurements were more valid, as most types of cores will cut off large pores or slickensides, which are the most active paths for conducting water under saturated conditions. Later, Bouma et al (9) directly addressed the problem of measuring water tables with unlined boreholes in these soils; shallow water table readings may be the result of preferential movement along voids into the boreholes, leaving the soil mass unsaturated. In the same article they recommended that with piezometers or, even better, with tensiometers there would be less probability that such voids would bring water into the bottom of the hole.

We could thus tentatively conclude that if we want only one operational definition of an aquic moisture regime for all soils we should adopt the piezometer or tensiometer method instead of the unlined borehole. An alternative could be to leave the unlined borehole for nonswelling soils and use the tensiometer for the soils under consideration.

A special problem could be presented for those Vertisols and other clayey cracking clays that are ponded for prolonged periods. In these the unlined borehole evidently does not apply or is rather cumbersome and uncertain. In using piezometers or tensiometers special attention would have to be paid to a good sealing around the tubes so that water from above the soil does not come in along the sides. Indirect evidence of saturation such as low redox potential, presence of reduced forms of Fe or Mn, or low chroma colors together with prolonged periods of ponding could also be used in an operational definition for those cases.

SOME PEDOGENETIC PROCESSES OF HYDROMORPHIC VERTISOLS

The most obvious and common pedogenetic process in all hydromorphic Vertisols is oxidation-reduction. There are apparently no field measurements of this process in Vertisols; only indirect evidence is available. Comerma

et al (15) reported quite a good relationship between poorly and very poorly drained classes in Vertisols based on periods of water ponding and low chroma colors (≤ 2) in the upper 50 cm, presumably reflecting reducing conditions. Ahmad (1) mentioned in his review on Vertisols the occurrence in some poorly drained Vertisols of Mn oxide nodules in the subsoil; he also suggested that hues of 2.5Y and 5Y could be used as indicators of wetness if accompanied by reddish and higher chroma mottles. One very important complication in the use of color as an indirect index of reduction in these soils is that many Vertisols, usually those of alluvial or lacustrine origin, may have gone through periods of intense reduction, producing low chroma colors that still remain, sometimes without reducing conditions. These circumstances were mentioned by Glazovskaya (24) in reference to a study of E. A. Kornblum in the USSR in which he postulated a process called "olivization" for the above situations in compact or Vertisol-like soils. Fitzpatrick (23) also mentioned that an important requirement for the formation of Vertisols is having periods of complete saturation and reduction as a condition for the formation of organic matter-clay complexes that produce the black colors. The above considerations point out the problematic use of low chroma colors in these soils as the sole index of reduction; there must always be assurance of prolonged periods of saturation accompanying the low chroma colors to be on the safe side. The use of field reagents to test for the presence of Fe^{2+}, like the one suggested by Childs (14), could also be of great help.

A second process that has been mentioned for poorly drained Vertisols is a higher accumulation of organic matter in the topsoil. Dudal and Moormann (19) stated that Aquerts in Southeast Asia have darker surface horizons and a somewhat higher content of organic matter than the better drained ones. In Venezuela Comerma et al (15) found average contents of organic matter of about 1% higher in the more poorly drained soils, but the ranges were similar to those of better drained classes, with quite an overlap.

A third process reported has been a textural differentiation or a clay increase with depth. In all cases mentioned one common characteristic is accentuated hydromorphic conditions, generally implying long periods of ponding. Bocquier (5) stated that waterlogging induces the loss of carbonates from the upper soil; then mobilization of Fe, migration of clay, and a net acidification are produced. Migration of clay plus silt and organic matter through cracks, called "flood coatings," have been mentioned by Brammer (12) to occur in similar situations. This last process has also been suggested by Moormann and van Breemen (29) to be en-

hanced by the hydraulic head of deep flooding and the removal of Fe as cement in the upper soil layers. Ferrolysis, as presented by Brinkman (13), has been postulated by Dudal (18) to occur in nonmulching Vertisols, including a loss of structure and a decrease in clay in the upper layers. Comerma et al (15) also found clay increases, with depth of about 10% or higher in Vertisols where flooding was quite prolonged and base saturation had been considerably lowered in the upper 50 cm. This acidification of the upper soil would suggest that desaturation precedes or occurs concurrently with either clay illuviation or clay decomposition, or both, through ferrolysis.

ICOMERT PROPOSAL ON TAXONOMY OF HYDROMORPHIC VERTISOLS

ICOMERT has been dealing with taxonomic problems in Vertisols since 1981 (27). At present it has a proposal on the subject of hydromorphic Vertisols that is the result of the opinion of several members of the Committee. This proposal includes a definition of an aquic moisture regime for Vertisols, a definition of a suborder Aquert, and the suggestion of three great groups, as follows:

- "Vertisols that have water stagnated at the surface or are water saturated in the upper 50 cm for prolonged periods of time" have an aquic moisture regime. This would include the two most common cases: a) Vertisols occurring in level areas subjected to ponding, and b) Vertisols in sloping areas but subjected to an external moisture regime or water seepage that produces saturation of at least the upper soil without ponding at the surface. The use of the tensiometer or piezometer rather than the unlined borehole would be recommended to prove water saturation.
- With respect to the definition of the suborder Aquert the proposal reads: Aquerts "have an aquic moisture regime or are artificially drained, and have in the upper 50 cm, if there is mottling, dominant moist colors, on ped faces, or in the matrix if peds are absent, with chromas of 2 or less; if there is no mottling have chromas of 1 or less."
- The proposed great groups in the key would be Dystraquerts, Planaquerts, and Eutraquerts. Dystraquerts would include Aquerts that have very low base saturation or are very acid at least in the major part of the upper 50 cm. Tentative criteria for acidity are taken from the proposition of G. Smith for acid families in

the Vertisols order, i.e., a pH in water of 5 or less which corresponds approximately to the significant appearance of Al in these soils or to a base saturation of 35% by sum of bases or 50% by CEC. Planaquerts (from the Latin planus -- flat or level) would have implied flat surfaces subjected to ponding and with a high base saturation. Eutraquerts would have a high base saturation and would most commonly be found in sloping areas without ponding but still saturated for long periods in the major part of the upper 50 cm.

RECOMMENDATIONS

The review of literature in this paper supports some of the proposals of ICOMERT, adds new and partial solutions to problems like the one of measuring water tables in swelling soils, and leaves certain problems unanswered. Among the most important subjects needing more detailed information is a careful monitoring of the moisture recharge of initially dry Vertisols, with the accompanying physical changes (swelling, pore size, bulk density, etc.) and the development of reduction stages around and inside peds. A carefully selected network of sites in which this monitoring would be carried out could be the basis of a simulation model that would summarize the relationships found between water movement and reduction; besides, the model could constitute an instrument for analyzing new situations among other Vertisols and could help answer questions about the probable periods of saturation and reduction in these soils. This modelling process has already started (26), covering infiltration; other complementary aspects must still be included. Another item that has to receive consideration is the sampling unit or pedon concept (41) as it applies to Aquerts that have gilgai, as only part of these soils show aquic regime characteristics. At present there are two possible solutions. One is to consider the depressed area of the gilgai as an Aquert and the shelf as nonaquic, i.e., considering them as two soils or as a complex mapping unit. The other solution is to consider the soil as an Aquert if more than half of the cycle is aquic, i.e., considering the situation as only one soil. The size of the cycle, as stipulated in Soil taxonomy, will also be included in the discussion.

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WET ALFISOLS WITH SPECIAL REFERENCE TO SRI LANKA

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Wet Alfisols of tropical regions are important soils for rice production. They are located mainly in areas with dry climates. In Sri Lanka, these soils are confined to dry and semidry lowlands. Most of them have an aquic or an anthraquic moisture regime. In this paper, the soil moisture regime encountered in the region where the wet Alfisols occur is considered in detail. The main processes that appear responsible for the formation of the wet Alfisols are wetting and drying, clay illuviation leading to textural differentiation, clay synthesis, accumulation of carbonates, reduction of Fe/Mn compounds, formation of stable Fe^{2+} compounds, and grayzation. Representative profiles of Aqualfs are described and the general properties are presented. The wet Alfisols are classified according to Soil taxonomy, and the problems of the classification are considered.

Wet Alfisols (Aqualfs) that have marked impressions on the morphology of a soil profile and distinct influences on the soil's chemical and physical properties arise from the conditions of excessive wetness.

In Sri Lanka, wet Alfisols are seasonally wet mineral soils that occur in association with well-drained Alfisols in the dry and semidry lowlands (3, 6, and unpublished reports of Land Use Division, Department of Irrigation, Colombo). All the soils of the Alfisol order, including wet Alfisols, are agriculturally very important in terms of their occurrence, management, utilization, and potential for agricultural development. Wet Alfisols are particularly important in Sri Lanka as in much of tropical Asia and Africa, because rice is produced on them (7).

The present trend in Sri Lanka is to concentrate other field crops on well-drained Alfisols while confining rice production to the wet Alfisols. The classification of the wet Alfisols and the character-

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ization of their chemical, physical, and morphological properties would be most useful in the assessment of the utilization potential in the introduction of new techniques of management, and in the development of improved rice production technologies.

PHYSICAL ENVIRONMENT

The position of the wet Alfisols in the landscape, the climatic environment, hydrological conditions, and human interventions to a great extent determine the soil's general character in Sri Lanka. A description of the soil's physical environment, though brief, may prove useful in the interpretation of their observable attributes.

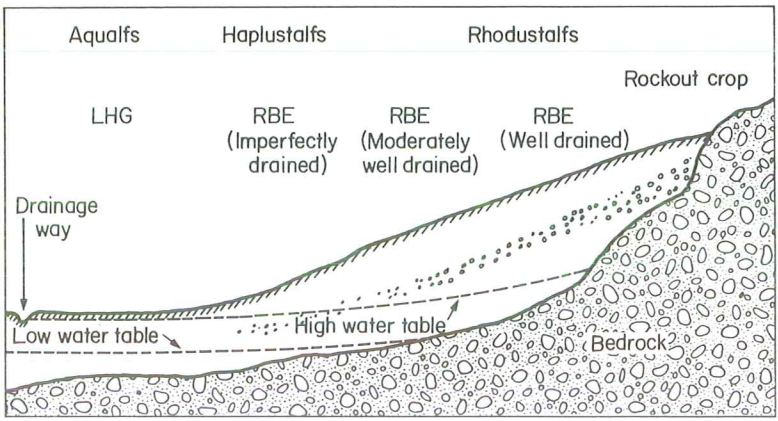
Physiography and landforms

The geomorphic setting of the wet Alfisols determines their profile characteristics as well as their management possibilities. Most commonly these soils are located in subdued parts of the landscape such as low plains and inland valleys. Three peneplain surfaces are associated with the three uplifts that have taken place during the geological history of the island. These peneplain surfaces are identified with the three land surface divisions based on elevation differences: 1) low-country, 2) mid-country, and 3) up-country. The wet Alfisols are confined to the low-country, the oldest peneplain surface.

The lowest peneplain surface can be subdivided into several natural regions, of which two units that fall within the dry zone and semi-dry intermediate zone -- the raised alluvial formations and the residual peneplain surface -- are important. Raised mudflats and alluvials are narrow level depositional surfaces occurring in narrow strips that merge imperceptibly with the semirecent clay plains along the seacoast and the residual peneplain in the interior. Within this formation are alkaline soils, which are also wet Alfisols (Natraqualfs). The residual peneplain, predominantly an undulating plain with some rolling portions, merges with the raised coastal plain. It is a featureless plain, except for occasional monadknocks. On this erosion surface or the etched plain is a moderately shallow, weathered mantle of rocks on which the Alfisols have developed. The wet Alfisols occupy mainly the lower slopes and valley floors of the numerous inland valleys in this residual plain (Fig. 1).

Climate

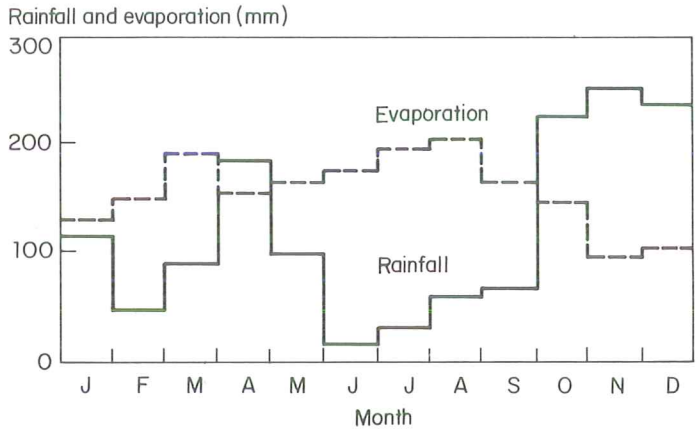
Climatic conditions within Sri Lanka are determined by its position in the Indian Ocean and by the central hilly and mountainous landmass, which interact to



1. Soil sequence in the landscape.

produce highly variable rainfall conditions throughout the country as well as the distinct seasonality of the rainfall.

Rainfall in Sri Lanka is both a regional and a local phenomenon. The monsoon rains, northeast from mid-November to mid-January and southwest from June to mid-September, occur as a regional phenomenon. The intermonsoonal convectional rains during March and April and again during September and October occur as a local phenomenon. The intermonsoon thunderstorms can attain maximum intensities of 26 mm in 8-15 min and 50 mm in 30-40 min in the lowland dry zone, as measured at the Maha Illuppallama Research Station. The annual rainfall distribution pattern is distinctly bimodal for most parts of the dry zone (Fig. 2). However, it is nearly unimodal in the eastern lowland region. The mean annual rainfall ranges from 1,500 mm in the wetter part of the dry zone to 875 mm in the drier part of the dry zone.



2. Mean monthly rainfall and evaporation in mm, Maha Illuppallama.

Hydrology

Rainfall is the most important input component of the hydrologic cycle in the dry zone. High intensity storms in the early part of the main rainy season produce a considerable overland flow into the valleys of the undulating landscape, and valley floors are subject to occasional flash floods. The incident rainfall on the upland infiltrates quite rapidly and flows into the valleys as interflow. The groundwater table in the valley rises quite rapidly and reaches the surface by about the middle of the rainy season. The runoff is also stored in minor reservoirs formed behind earthen dams built across the valleys. The system of reservoirs and the irrigation of the valley soils contribute to the maintenance of high water tables for at least 5-6 months in the year. Upon natural conditions, the high groundwater levels recede much earlier, usually in 3 months. All streams except those that receive drainage water from irrigated areas and minor reservoirs run during the dry weather.

Soil parent material

In the residual peneplain, the soils have developed on the weathered and somewhat dislocated products of pre-Cambrian rocks. These very ancient rocks have been separated into two main groups, the Khondalite or Highland series and the Vijayan series (2). Highly mixed groups consisting of charnockites, garnet-sillimanite schists and gneisses, quartz schists, and quartzites form the Khondalite series, while hornblende gneisses, biotite gneisses, metasediments (mainly calc-gneisses) associated with pegmatites, and migmatites constitute the Vijayan series. The soils derived from weathered products of the Highland series are finer textured.

Vegetation and land use

The natural vegetation throughout the dry zone is a dry mixed evergreen forest. Most of the tree species are semideciduous. The main species are Wira (Drypetes sepiana), Palu (Manilkara hexandra), and Burutha (Chloroxylon switenia). All the soils of the Alfisol order, including the wet Alfisols, have similar natural vegetation. Wherever the primary vegetation has been cleared for shifting cultivation, secondary vegetation or scrub jungle appears within 3-4 years after the land is abandoned by the farmer.

Land use on wet Alfisols in Sri Lanka is distinct. Almost all these soils in inland valleys and raised alluvial terraces have been developed into bunded rice fields. Commonly, the inland valley soils are puddled, rice is planted, and standing water is maintained during the growing period.

Soil moisture regime

The soil moisture regime of wet Alfisols in Sri Lanka is determined by their location in the landscape and the prevailing climatic conditions. Most wet Alfisols have an aquic moisture regime, as defined in Soil taxonomy (12), implying a reducing regime that is virtually free of dissolved O_2 because the soil is saturated by groundwater or by water of the capillary fringe. The Alfisols in the valleys and lower concave slopes of the residual peneplain and those on raised alluvial terraces along the coast have high groundwater to saturate the soil profile for such lengths of time that characteristics of intensely reducing conditions are present; the soil colors are gray or neutral gray in all horizons below the Ap or A_1.

There are other Alfisols that have a high groundwater table for a shorter duration than in the valley bottoms. They occur in the phreatic zone and have a high groundwater table during the rainy season. The water table reaches the surface in mid-November and remains there for at least 30 consecutive days (10). However, these soils show higher chromas than those of intensely reduced horizons. The gray or neutral gray colors are present at approximately 75-cm depth. Commonly, they can be considered wet because of the artificial aquic moisture regime resulting from the cultivation of wetland rice under puddled conditions and inundation during the crop season. They may be saturated with water for as long as 210-240 days in the year when rice is double-cropped. The subsoils have mottling and gleying in addition to the surface water gley.

The well-drained Alfisols in the same region have an ustic moisture regime, but some Ustalfs may be considered wet because of the artificial wetness created by the puddling and inundation for rice culture. However, the moisture regime cannot be considered aquic. In some of these irrigated Ustalfs there is only the surface water gley; the subsoil shows no evidence of reducing conditions.

Soil temperature regime

Air temperatures in the Alfisols region of Sri Lanka vary only slightly through the seasons and through the day (Table 1). The temperature fluctuations in the soil

Table 1. Mean monthly air temperatures, Maha Illupallama, 1974-1982.

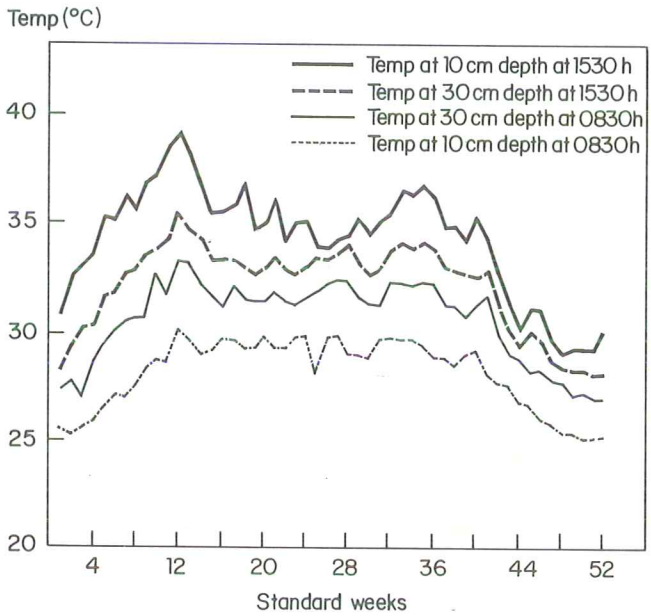
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	24.7	25.8	27.6	28.4	28.3	28.2	28.4	28.5	27.3	25.9	24.9	24.9
Maximum	29.1	31.1	33.4	33.6	32.4	32.2	32.5	32.9	33.1	31.7	30.0	28.7
Minimum	20.4	20.4	21.7	23.2	24.4	24.4	24.0	24.0	23.8	22.9	21.8	21.1

medium at depth depend on several factors such as the heat capacity of the soil, porosity, and water content. For wet Alfisols that are water saturated, no soil temperature data are available, therefore data obtained for well-drained soils are used here. It is well-accepted that temperature fluctuates less in wet soils than in well-drained soils.

Soil temperatures measured at the Maha Illuppallama Agriculture Station are shown in Figure 3. The soil temperature at 30 cm shows a smaller diurnal range than that at 10 cm. The daily variations would be even smaller at 50 cm, than at 30 cm. The temperature difference between the summer months (June, July, August) and the winter months (November, December, January) is 3.3°C at 0830 h and 3.0°C at 1530 h. The temperature difference between the hot, dry months and the cool moist months at 50 cm would be even less than 3°C. The soil temperature regime of the wet Alfisols would therefore be isohyperthermic.

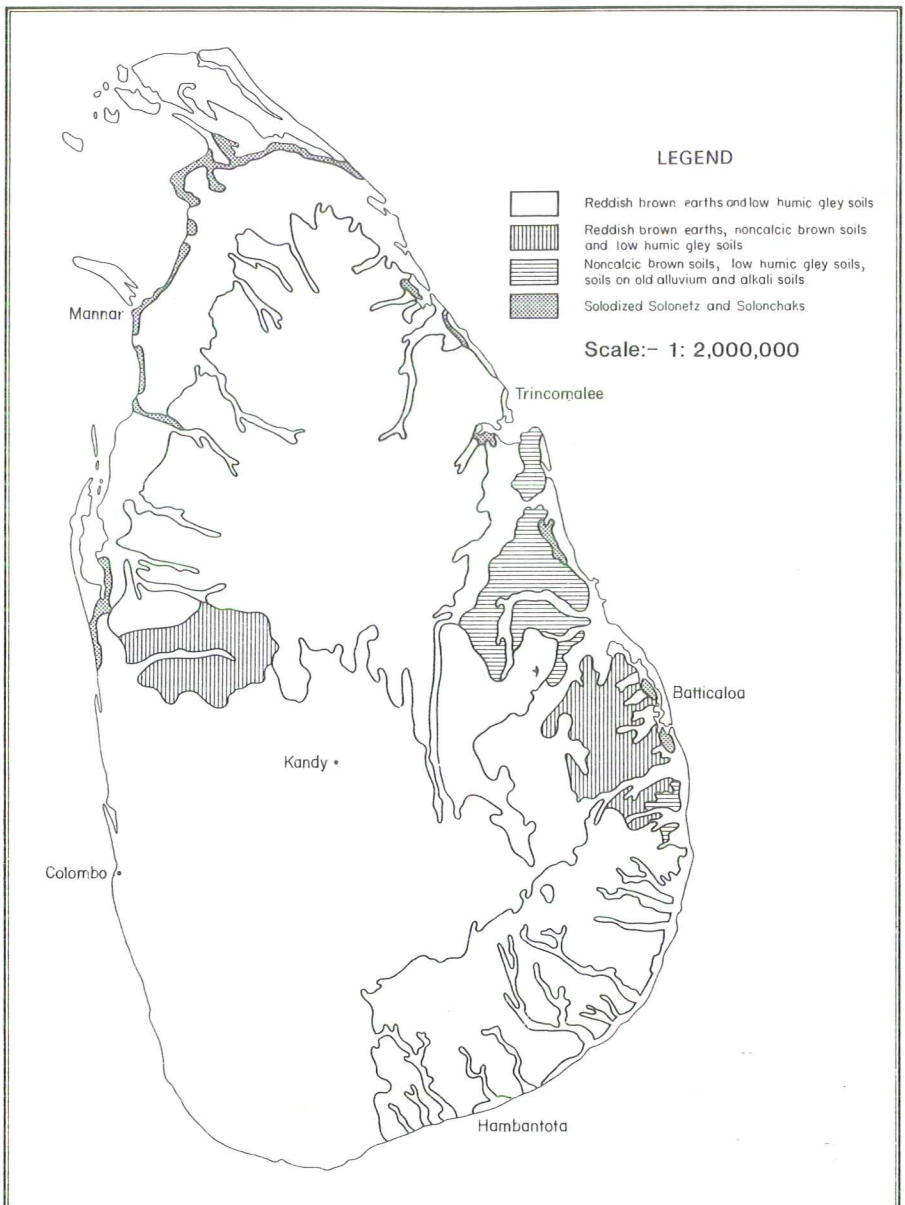
DISTRIBUTION

The distribution of Alfisols is shown in Figure 4. The great groups identified within the shaded area are soils of the Alfisol order with inclusions of the great groups of the Aquent and Aquept suborders. The wet Alfisols and the well-drained Ustalfs occur in close association where the wet Alfisols are confined to the



3. Soil temperature at 10-cm and 30-cm depths at 0830 h, and 1530 h Maha Illupallama, 1978-80.

lower slopes and valley bottoms (Fig. 1). The other wet Alfisols, namely Natraqualfs, occur commonly on the raised alluvial terraces along the coastal plain and at interflow sites of valleys where salinity and alkalinity have developed. The total extent of wet Alfisols is 25-30% of the Alfisols area.



4. Areas containing wet Alfisols in Sri Lanka.

SOILS AND SOIL PROPERTIES

The wet Alfisols have been studied quite extensively in the field (unpublished reports, staff, Land Use Division, Colombo, 1960-1983). In addition to the soils of the Aqualf suborder, there are other Alfisols that are wet because of irrigation, seepage, or phreatic conditions. The Alfisols found within the phreatic zone of the slopes of the dry zone have groundwater tables close to the surface during the rainy season, though they may recede quite rapidly with the termination of the rainy season. Seepage from irrigation channels and irrigated upland areas enhances the groundwater build-up in the phreatic zone and the soils remain wet. Then there are the Ustalfs that are wet because of irrigation and cultivation of wetland rice under puddled conditions.

Several authors have desribed the soils of the Aqualfs suborder in Sri Lanka (6; unpublished reports, staff, Land Use Division, Department of Irrigation, Colombo, 1960-1983). The common morphological properties of these soils are:

- Texturally contrasting horizons;
- Textural B horizon, usually with evidence of clay illuviation in the form of clay bridges and cutans;
- Very hard or extremely hard surface soil when dry in "normal" Aqualfs;
- Presence of Natric horizon in some Alfisols;
- Presence of gleying in the whole profile;
- Slightly acid to slightly alkaline soil reaction;
- A subsoil horizon of carbonate accumulation; and
- High base saturation, normally 60-100%.

These Aqualfs are characterized by a dominantly dark gray brown to brown color on the surface and gray, gray brown, or neutral gray colors in the subsurface horizons. The textures range from sandy loams to loamy sands at the surface and sandy clay loams to sandy clay in the subsoil horizons. They have a weakly to moderately developed coarse medium subangular blocky structure in the subsurface horizons. Strongly mottled as well as gleyed horizons occur at variable depths. A horizon with $CaCO_3$ concretions is encountered at about 1 m from the surface. Aqualfs of Sri Lanka have generally good chemical properties (Table 2). The soils are slightly acid to alkaline in reaction. The cation exchange capacity ranges from 25-30 meq/100 g soil while the base saturation is high (70-100%) in the subsoil. The soils contain a fair proportion of weatherable minerals. Organic matter in the surface horizons ranges from 1 to 4%. The available moisture-holding capacity is low, the values ranging from 12 to 20% by volume. The infiltration rates are as low as 2.5 mm/h up to 25 mm/h after 4 h.

Table 2. Important soil properties of the Alfisols in Sri Lanka.

Soil	Texture surface	pH	CEC (meq/ 100 g)	Base saturation % (meq/ (100 g)	C (%)	C:N	Available moisture (mm/m)	Av intake rate after 4 h (cm)
Rhodustalfs	Sandy loam to Sandy clay loam	5.5-7.0	10-20	60-90	0.5-2	8-12	132-166	2.7-9
Haplustalfs	Sandy loam to Sandy clay loam	5.2-6.5	8-12	50-70	0-2	8-12	120-150	2.7-12
Tropaqualfs	Sandy loam to Sandy clay loam	5.5-6.5	15-30	70-100	1-4	7-8	120-196	0.3-2.5
Natraqualfs	Loamy sand to Fine sandy loam	7.0	15-30	100	0-2	10-15	—	low

Soil profile descriptions

Profile descriptions of two Aqualfs developed from two different parent materials are as follows:

- Aqualfs developed from parent material derived from the Khondalite series of rocks. The soil is classified as a Vertic Tropaqualf.

  A_p 0-13 cm; dark yellowish brown (10 YR 4/4) with dark grayish brown (2.5 Y 4/2) spots and redder root mottles; sandy loam with thin clayey and sandier layers due to puddling; weak medium subangular blocky; slightly sticky; slightly plastic; friable; many fine vesicular and tubular pores; many fine roots with a concentration in the first 4 cm; clear smooth boundary.

  B_{2tg} 13-33 cm; dark grayish brown (10 R 4/2) sandy clay loam; common medium distinct dark yellowish brown (10 YR 4/4) mottles; moderate fine subangular blocky; sticky; plastic; firm when dry, broken thin clay skins; common fine tubular pores; few fine hard black Fe/Mn concretions; clear smooth boundary.

  IIB_{3tg} 35-59 cm dark gray (5Y 4/1) clay with common fine yellowish brown mottles; moderately coarse angular blocky, sticky, plastic; very hard when dry, common vertical cracks up to 5 mm wide; common distinct pressure faces; common fine Fe/Mn nodules and dark stains; few fine roots mainly in ped surfaces and pressure faces; clear smooth boundary.

  IIC_gCa 59-110 cm +; dark gray (5Y 4/1) clay with common fine yellowish brown mottles and many irregular whitish spots due to lime concretions and nodules; moderate coarse angular blocky; sticky; plastic, very hard, some pressure faces; common fine inped pores; $CaCO_3$ concretions and nodules are from 2 to 15 cm in diameter; few fine roots.

- Aqualfs developed from parent material derived from the Vijayan series of rocks. The soil is classified as a Typic Tropaqualf.

  A_p 0-12 cm; dark grayish brown (2.5Y 4/2) sandy loam; structureless, single grained, nonsticky, nonplastic; many fine roots; common medium and coarse pores; clear smooth boundary.

  A_3 12-25 cm; dark gray (5Y 4/1) sandy loam; weak fine subangular blocky, nonsticky, nonplastic; common medium and coarse pores; many fine roots; clear, smooth boundary.

  B_1 25-58 cm; dark gray (5Y 4/1) sandy, weak medium subangular blocky, slightly sticky, slightly plastic; common medium and coarse pores; many fine roots; clear smooth boundary.

  B_2 58-75 cm; dark gray (5Y 5/1) sandy loam; few fine faint mottles; weak medium subangular blocky; few fine roots; clear smooth boundary.

  B_{22} 75-90 cm; dark gray (5Y 5/1) sandy clay loam; weak medium subangular blocky; slightly sticky, slightly plastic; few fine roots.

Natraqualfs occur in raised alluvial terraces at the margins of the residual peneplina. These soils are minor in extent, distribution, and utilization. The following is a representative profile of the great group of Natraqualfs:

- Profile description of a Natraqualf.

  A_{pg} 0-14 cm; grayish brown (2.5 Y 5/2), few fine distinct dark reddish brown mottles, indistinct root mottling; sandy clay loam with thin discontinuous layers and lenses of sandier and more clayey material due to puddling; weak medium subangular blocky; slightly sticky, slightly plastic, very hard when dry; common fine interstitial pores; many fine roots; clear smooth boundary.

  A_{2g} 14-31/42 cm; light gray (2.5 Y 6/1) sandy clay loam with common medium to fine distinct dark yellowish brown mottled and faint, brownish streaks; weak medium subangular blocky; slightly sticky, slightly plastic, firm and hard when dry; common fine tubular and interstitial pores; occasional clay lining of tubular pores; few fine Fe/Mn nodules; few fine roots; locally thin bleached sandy layers tonguing in underlying horizons; clear wavy boundary.

  $B_{2t(g)}$ 31-42-46/56 cm; yellowish brown (10 YR 5/5) matrix with gray spots and streaks and few fine faint reddish mottles; sandy clay; moderate, coarse columnar, composed of weak

subangular blocky peds, very thin sandy layers at many places between adjacent columnar peds, and on top of the columns; sticky, plastic, firm, very hard when dry; many intersecting slickensides; thin broken clayskins, best expressed in pores many fine tubular pores showing a dendritic pattern on slickensides (root channels); few fine Fe/Mn concretions; few fine roots; gradual wavy boundary.

$11B_{tg}$ 46/83 cm; light gray (2.5 Y 6/1) matrix with common medium prominent clear reddish (e.g. 2.5 YR 4/6) mottles; sandy clay; continuation of the columnar structure units, composed of weak angular blocky peds; sticky, plastic, extremely firm, very hard when dry; fewer slickensides than above.

SOIL-FORMING PROCESSES

The main processes that seem active among wet Alfisols are seasonal wetting and drying, fluctuating water table, textural differentiation and clay illuviation, grayzation, clay synthesis, accumulation of carbonates, and possible mobilization of Fe and Mn.

Wetting and drying

Alfisols are distributed in areas where the dry period is distinctly protracted. Seasonal wetting and drying of these soils is a distinct process. The rainfall, temperature, and evaporation conditions are such that during the cool months the incident rainfall is very much in excess of evaporative demand (Fig. 2). Wet Alfisols remain wet because of the high rainfall and interflow and surface flows or the phreatic water and fluxial conditions.

During the long hot, dry period, the whole soil profile dries out well below the permanent wilting point. In the Alfisols region, without irrigation the total dry days range from 150 to 210 of which more than 90 days are consecutively dry. In irrigated soil, seasonal wetting and drying is still an active process, because most of the irrigation occurs during some part of the rainy season to supplement the incident rainfall.

During the drying cycle, the soils crack sometimes to depths of 50-60 cm. Cracking of the surface soil is most prominent on finer textured Aqualfs. In the wetting cycle, because of the ready slaking of the soil aggregates and the impact of raindrops, the clay in the surface soil is dispersed and moves through the cracks into the subsoil layers. Furthermore, the clay that is in suspension is sucked into the subsoil horizons because of the high moisture tensions developed in the drying cycle.

Fluctuating water table

A seasonally high groundwater table occurs in the rainy season in locations where wet Alfisols are normally found (8). In the dry season the water levels recede by 1-2 m. Numerous observations (unpubl.) suggest the occurrence of two cycles of fluctuation of the groundwater table. One is the seasonal fluctuation that is primarily related to the annual rainfall distribution pattern; the other fluctuation is related to the rainfall distribution within the rainy season. Furthermore, water table fluctuations in undulating terrain are closely related to position in the landscape and alluvial terrace plains. They are closely linked to regional drainage and/or profile drainage conditions.

Wet Alfisols remain waterlogged when the water tables are high for sufficiently long periods to cause reducing conditions. At low groundwater levels the solum above the influence of the groundwater acquires oxidizing conditions and at least part of the reduced ions are reoxidized. The alternation of oxidation and reduction in wet Alfisols (8) produces distinctive morphological features such as separation of Fe and Mn horizons, development of mottled zones, and formation of concretions.

One of the main effects of the water table in wet Alfisols is its influence on clay movement in the profile. In the climatic regions where wet Alfisols occur, the groundwater is charged with bivalent cations; therefore the clay that moves in a dispersed state is readily flocculated and precipitated at contact with the rising water table. The fluctuating water table enhances clay accumulation in the subsoil, but the formation of well-developed clay skins may be retarded. Sometimes, the presence of indistinct clay skins in the argillic horizons of wet Alfisols may be due to such clay flucculation.

Textural differentiation and clay illuviation

The subsoil horizons of the Aqualfs studied (6; Staff, Land Use Division, Department of Irrigation, Colombo, 1960-83) have sufficiently high quantities of clay that their B horizons qualify as Argillic. Weakly developed clay skins (cutans) and clay bridges are commonly observed in some parts of or throughout the B horizon. Information other than field observations, such as from micromorphological studies, is not yet available to support clay illuviation as a dominant process in Sri Lanka or other tropical countries.

However, the low clay content of the surface horizons is distinct and cannot be due entirely to processes of selective destruction of clay in the

surface soil layers. Though seasonal wetting and drying is a prerequisite for ferrolysis, a process of dissolution of clay in surface soils in lowlands (1), the base saturation status of wet Alfisols, and the high concentrations of Ca^{2+} and Mg^{2+} in the soil solution may not permit the entry of Fe^{2+} into the exchange sites to facilitate acid attack on the silica alumina bonds. In Aqualfs cultivated for wetland rice under puddled conditions, clay movement would be enhanced by the presence of cracks and pores. This has been an active process of clay transfer (7).

Grayzation

All Aqualfs show evidence of intense reduction of Fe^{3+} to Fe^{2+} and development of a gray or neutral gray color with or without mottling. The location of the Aqualfs is such that the groundwater table is fed from the uplands by the subsurface flow of water. Therefore the soils acquire a permanent gley or gray color because of the reduction of Fe^{3+}. During the drying cycle, the gray colors do not change into redder or yellower hues in spite of the good aeration, indicating the stable nature of the reduced Fe compounds that have formed (5). Pseudogley-like horizons are formed on soils that are irrigated and that have surface saturation conditions for shorter durations, as in the case of imperfectly drained soils.

Clay synthesis

Unlike in well-drained Ustalfs, in the associated Aqualfs strongly developed clay skins (cutans) are lacking and clay illuviation appears less pronounced. However, the clay content in the subsoil horizons of the Aqualfs is quite high. The most common range of clay contents on the B horizons of Aqualfs is 20-35%, whereas in Ustalfs with strong clay illuviation it is 15-35%. These soils have high concentrations of Ca^{2+} and Mg^{2+}. Their available Si is over 600 ppm (9). The cation exchange capacity of the clay, 50-100 meq/100 g soil, indicates the presence of fairly high quantities of 2:1 lattice clays, whereas the clay in the B horizon of Ustalfs is dominantly of the 1:1 type. Thus, it appears that clay synthesis in the Aqualfs is an important process. From a study of soil mineralogy of a toposequence, it was found that 2:1 lattice clays increased downslope (R. Senevirathna, pers. comm.).

A high proportion of smectites in the clay fraction of wet Alfisols was found (J. Handawala, unpubl. Ph D thesis, Maha Illuppallama) whereas the associated Ustalfs contained only traces or no smectites, supporting the view that in wet Alfisols there is synthesis of clay and, possibly, weathering has a lower intensity than weathering by climatic factors.

Accumulation of carbonates

In Sri Lanka, most of the Aqualfs have a horizon of carbonate accumulation below the B horizon. The morphology of the horizon of carbonate enrichment and the form of the carbonate nodules and concretions indicate their secondary origin. In spite of the seasonally high rainfall, the soil of wet Alfisols is not very well leached. The infiltration of wet Alfisols is quite low; after 4 hours, the average intake ranged from 0.3 to 2.0 cm/h compared with 2.7-9 cm/h for the normal, well-drained Ustalfs (11). During the rainy season, high groundwater levels are maintained by subsurface flow (interflow) from adjacent uplands, and this water is charged with bases and salts. The dominant cations in the soil solution are Ca and Mg, as evident from groundwater quality data (Mahaweli Ganga Development Project, 1972, unpubl. data). In the wet season, the groundwater moves upward, while evapotranspiration withdraws the soil water and leaves the carbonate behind. During the dry season, the withdrawal of soil water for evapotranspiration is high enough to precipitate carbonates in the subsoil. Wet Alfisols in the phreatic zone do not have a zone of carbonate enrichment and there are no signs of any accumulation of carbonate in irrigated Ustalfs.

Mobilization of iron and manganese

In Aqualfs, mobilization of Fe and Mn and precipitation in distinct layers do not constitute a dominant process. Similar observations have been made elsewere (7). It is very likely that reduced Fe exists as stable complexes locked in intensely reduced zones of soils, a view supported by some studies in Japan (5). In soils whose wetness is due to irrigation or to seepage in the rainy season, the migration of Fe and Mn from the surface water gley horizons is a dominant process. In these soils, below the surface water gley horizon is an aerated subsoil with adequate potential for oxidation of Fe^{2+} and Mn^{2+}. The reduced Fe and Mn, when percolated into the subsoil layers, are precipitated because of oxidation and the sparingly soluble nature of the oxides. Thus, distinct layers of Fe and Mn are formed. This behavior of Fe and Mn on irrigated, well-drained soils has given rise to the concept of Aquorizem (4).

CLASSIFICATION OF WET ALFISOLS

A number of soil classification systems have been developed in various countries, some of them internationally recognized. Widely used systems are the FAO/UNESCO Legend of the Soil map of the world and Soil taxonomy. In the early sixties, the soils of Sri

Lanka were classified on the basis of soil morphology (6), and 14 great soil groups were identified in 17 mapping units (Fig. 5). The present trend in Sri Lanka is to classify soils according to the system of Soil taxonomy, which is very useful in that most identified soils of Sri Lanka can be classified and new taxa can be added if and when necessary.

Alfisols have the following combinations of properties.

- an argillic horizon but not excessively leached; base saturation over 35%;
- no spodic or oxic horizon underlying the B horizon;
- no mollic epipedon;
- an epipedon that is both massive and hard or very hard when dry; or an aquic, udic, or ustic moisture regime.

According to the system of Soil taxonomy, the wet Alfisols in Sri Lanka can be classified as shown in Table 3.

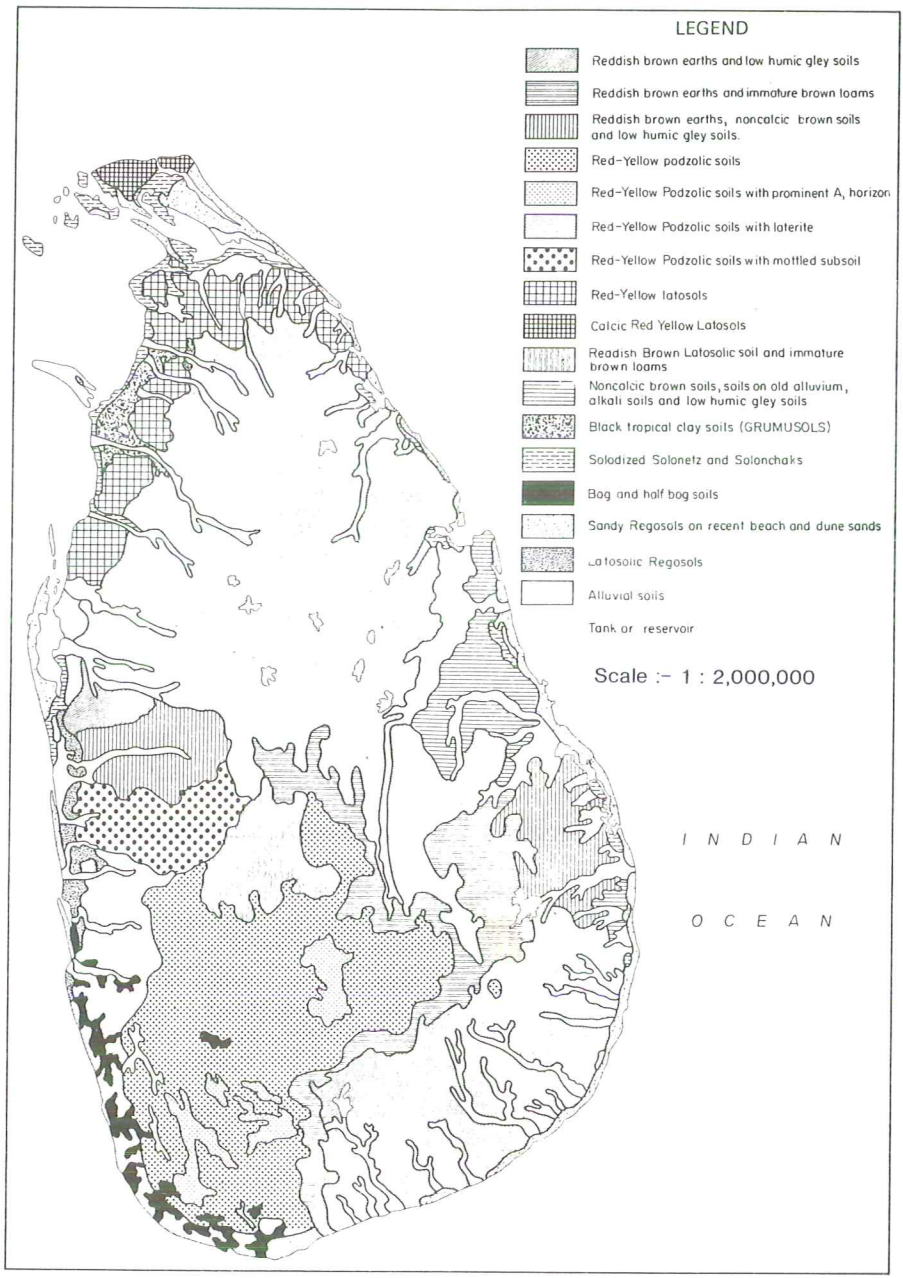
Normal wet Alfisols are the soils of the Aqualfs suborder. However, irrigated well-drained Ustalfs under wetland rice have a saturated moisture regime for at least 90-180 days/year depending on the cropping intensity. But the wetness does not leave any marks of reducing conditions on the Rhodustalfs. The maximum effect observed is a change from redder to brown colors in the surface.

Reddish brown earths (brown subgroup), the Aquic Haplustalfs, have definite marks of wetness when irrigated. Because of both puddling and inundations, in addition to seepage from the irrigated uplands, the soils acquire a reducing moisture regime. In the profile, low chroma mottles are evident in the B horizons. The surface water gley is observed in most irrigated Haplustalfs. Therefore these soils are classified as Anthraquic or Aquic Haplustalfs.

PROBLEMS IN CLASSIFICATION OF THE WET ALFISOLS

A major concern is the identification of the textural B horizon with the "argillic" horizon as defined in Soil taxonomy. In an argillic horizon, there is a significant accumulation of illuvial clay. In soils classified as Aqualfs in Sri Lanka, distinct marks of clay illuviation are not present, as in well-drained Alfisols. The content of illuvial clay, residual clay, and clay synthesized in situ cannot be partitioned. Thus a serious doubt is cast on the identification of the textural B horizon with the argillic horizon that forms by the accumulation of illuviated clay. On the other hand, a further complication occurs because clay transferred downward by rainwash is constantly added to

the surface layers of the Aqualfs, resulting in smaller clay increases in the B horizon than in the surface layers even though the B horizon accumulates sufficient illuvial clay to justify its identification with an argillic horizon. Some of the Haplustalfs acquire the morphological properties of normal Aqualfs upon



5. Generalized soil map of Sri Lanka.

Table 3. Important wet Alfisols and Sri Lankan national equivalents.

Soil order	Suborder	Great group	Subgroup	National equivalent (6)
Alfisols	Aqualfs	Natraqualfs	Typic Natraqualfs	solodized solonetz
		Tropaqualfs	Typic Tropaqualfs	low humic gley
			Aeric Tropaqualfs	low humic gley
			Vertic Tropaqualfs	low humic gley
	Ustalfs	Rhodustalfs	Anthraquic Rhodustalfs	reddish brown earths
		Haplustalfs	Anthraquic Haplustalfs	non-calcic brown soils
			Aquic Haplustalfs	reddish brown earths (brown subgroup

irrigation. A profile placed in the aquic subgroup before irrigation may be placed in the Aqualfs suborder after irrigation, differentiating the taxa on cultivation.

Most other criteria seem adequate for placing the wet Alfisols in the different categories of the system. However, a major problem is the need for evaluation and quantification of many soil characteristics to classify them according to Soil taxonomy.

UTILIZATION AND MANAGEMENT

In all wet Alfisols in Sri Lanka, rice is cultivated in one or two seasons in a year, with or without irrigation. These soils, except for Natraqualfs, have a high production potential, the Aqualfs being ideally suited for rice culture as practiced in Sri Lanka. The conditions for tillage are best when the soils are water saturated; the soils are puddled and leveled for planting rice. Standing water is maintained through the growing season. For high yielding rice varieties, fertilization and weed control are essential on these Aqualfs.

Wet Alfisols (anthraquic) of the Ustalfs suborder are good for dry food crops under irrigation in the dry season. In the dry period, most subsidiary food crops are grown on these soils. However, during the rainy season, these soils develop aeration problems, with or without irrigation. Their tillage is best performed when they are moist, near field capacity. They are highly erodible because of low organic matter and poor structural stability.

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WET ANDISOLS

K. KYUMA and M. MITSUCHI

Problems related to the classification of wet Andisols are discussed with particular reference to Andisols with an aquic moisture regime occurring in Japan. A specific feature of wet Andisols, compared with other wet soil taxa, is that the characteristics associated with wetness, such as gray color and mottles, are much less conspicuously expressed in Andisol profiles. Therefore, a simple field test, e.g. a dipyridyl reaction to detect active Fe^{2+}, in addition to the ordinary characteristics should be adopted as a criterion to confirm wetness. Another point to be noted is the high organic matter content of some wet Andisols, which satisfies the requirement of organic soil material for wetness. As the nature of the organic matter in such a soil is entirely different from that of ordinary organic soil material, the two must be distinguished from each other through use of certain indices of the degree of humification of the soil organic matter. The characteristics of the naturally occurring wet Andisols and those of "anthraquic" Andisols, which are induced by artificial submergence for rice cultivation, are examined. Criteria of "anthraquic" subgroups in general, including Andisols, are also tentatively proposed.

A tentative definition of Andisols as the proposed 11th order in Soil taxonomy reads as follows (2):

> Andisols are mineral soils that do not have an argillic, natric, spodic, or oxic horizon unless it is a buried horizon occurring at a depth of 50 cm or more, and which have soil material beginning at, or within 25 cm of the surface, in which all subhorizons have andic and/or vitric soil properties throughout a continuous thickness of 35 cm or more.

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Obviously, this definition replaces that of Andepts as a suborder of Inceptisols in the present system of U.S. soil classification.

"Andic" and "vitric" soil properties are tentatively defined as follows:

Soil material with andic soil properties has:

- a bulk density at 1/3 bar water retention of the fine earth fraction of less than 0.9 g/cm^3;
- a phosphate retention value of more than 85%; and
- either an acid oxalate extractable Al value of 2.0% or more or a 4 M KOH extractable Al value of 1.5% or more.

Soil material with vitric soil properties has:

- more than 60% by volume of the whole soil as cinders, pumice, or pumice-like material or more than 40% by weight of the sand fraction (0.05-2 mm) as volcanic glass; and
- either an acid-oxalate extractable Al value of 0.4% or more or a 4 M KOH extractable value of 0.3% or more.

Although some of the criteria have been revised or made more precise or even newly set in the light of recent research results, these definitions are basically conformable to the present definition of Andepts.

Thus, we may be able to say that Andisols are almost equivalent to Andepts. The only clear difference between the two resides is the exclusion or inclusion of soils with an aquic moisture regime. Andepts exclude andic or vitric soils with an aquic moisture regime, which are placed under the Aquepts suborder as Andaquepts, whereas Andisols do include them, though still tentatively, in the Aquands suborder.

In this paper we will discuss the morphological characteristics and the classification of "wet" Andisols. Here we use the word "wet" to include not only Aquands but also aquic subgroups of other Andisols and even "anthraquic" subgroups, which occur quite widely in paddy or lowland rice-growing areas. Our discussions will be based on Japanese experience and knowledge, information from elsewhere being scanty and unavailable to us.

FIELD OCCURRENCE AND MORPHOLOGICAL CHARACTERISTICS OF WET ANDISOLS WITH AQUIC MOISTURE REGIME

The occurrence of wet Andisols with an aquic soil moisture regime at some depths of a profile is conditioned by the following two elements:

1. Occurrence of materials with andic or vitric soil properties or both
   a) primary formation from aeolian deposits

(mainly volcanic ashes and pumices) or from pyroclastic flow deposits (mainly pumice flow)

b) secondary fluvial deposition of materials formed elsewhere

2. Occurrence of aquic moisture regime
   a) low-lying lands
   b) uplands with impeded drainage

The most frequently encountered combinations in which wet Andisols occur would be the following two; 1a + 2b, formation of Andisols from primary aeolian or flow deposits resting on terraces or fans with impeded drainage; and 1b + 2a, secondary deposition of materials of andic or vitric soil properties in small floodplains and narrow valley bottoms, or both. The combination of 1a + 2a, direct-fall or flow deposits in the lowland, is not widespread but occurs in the vicinity of active volcanoes. Often aeolian and fluvial deposits alternate in such an environment to result in a 1a/1b + 2a type. Another combination, 1b + 2b, is also relatively rare, occurring in depressional parts of terraces with gently undulating topography.

Several profiles that correspond to the various occurrences given above are described and their characteristics are discussed. Profile characteristics are reproduced in Figures 1-7. The horizon nomenclature is given according to the original descriptions. A few relevant data to prove andic or vitric nature are also given.

Profile 1 (Fig. 1, originally described by Mitsuchi, unpubl.)

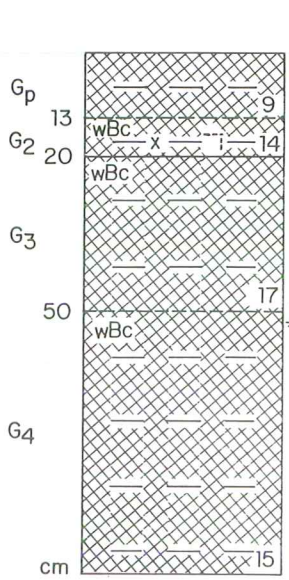
Location: Shimotakanezawa, Haga-cho, Tochigi Prefecture

Topography: level valley bottom between dissected terraces

Parent material: river alluvia dominated by redeposited andic materials

Land use: paddy field

Profile 1 is an example of the 1b + 2a type of occurrence. The soil is characterized by a strongly black color, high organic matter content, low bulk density, and high phosphate sorption capacity throughout the profile to a depth of more than 1 m. In short, it is a typical Andisol with andic properties. The soil has a few to many thread-like and filmy Fe mottles to a depth of only 20 cm, thought to be an effect of rice cultivation. If the soil had not been used as a paddy field, no mottles would have been formed throughout the profile even if the soil has an aquic moisture regime for many months of the year. The presence of the aquic moisture regime was proven by the Fe^{2+} reaction with α,α'-dipyridyl reagent. The reaction was quick and clear for the second to fourth horizons, but slightly less clear for the surface horizon.



	OM (%)	BD (g/cc)	P-sorption (a)	(BM)	NaF
10YR 2/1,CL	14.3	0.51	1960	86.0	10.3
10YR 2/1,CL	14.4	0.55	1990	89.8	10.5
10YR~2.5Y2/1,CL	15.3	0.56	2030	91.6	10.6
10YR~2.5Y2/1,CL	16.7	0.50	1810	85.8	10.1

1. Schematic sketch of Profile 1 and its properties.

Mottles shape

X thread-like ferruginous mottles along root channels
∫ tubular ferruginous mottles along root channels
⌝ filmy ferruginous mottles on ped faces and cleavage planes
* cloud-like ferruginous mottles in the matrix
● spotty manganiferous mottles in the matrix
\+ thread-like manganiferous mottles along root channels

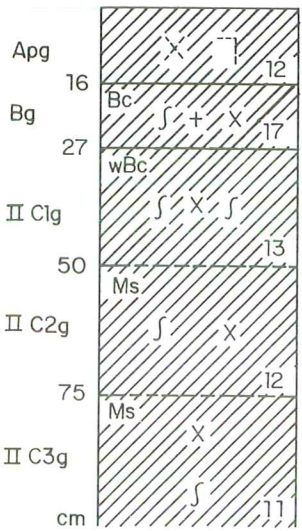
abundance: X few, XX common, XXX many, XXXX abundant
contrast: X⌝∫ prominent-distinct, X⌝∫ clear-faint

Organic matter: >10%, =10-5%, =5-2%, < 2%

Structure: Bc = blocky, Cr = crumb, Gn = granular, Ms = massive, Nt = nutty, Pl = platy, Sg = single grain, w = weak, vw = very weak

Horizon boundary: abrupt, clear, gradual, diffuse, not described, wavy

Other symbols: gleyed horizon with dipyridyl reaction. Numerals in the lower right corner of each horizon are Yamanaka's hardness meter reading in mm.
○ rounded gravels, □ angular gravels.
(a) P-sorption capacity measured using 2.5% $(NH_4)_2HPO_4$ (pH 7) in soil-solution ratio of 1:2, in mg P_2O_5/100 g.
(BM) P-sorption capacity measured by Blakemore's method using 0.439% KH_2PO_4 (1000 ppm as P) at pH 4.6 in soil-solution ratio of 1:5, in % adsorbed.
(b) P-sorption capacity measured using 0.1 N Na_2HPO_4 (pH 7) in soil-solution ratio of 1:10.



		OM (%)	BD (g/cc)	P-sorption (a)	P-sorption (BM)
Apg	10YR3/2,CL	7.90	0.63	1700	78.1
Bg	10YR~2.5Y 3/2,CL	6.24	0.71	1770	81.4
II C1g	10YR 2.5/1,LiC	6.67	0.64	1920	82.6
II C2g	10YR 1.7/1,HC	5.72	0.57	1980	62.6
II C3g	10YR1.7/1,HC	5.42	0.54	1780	53.9

2. Schematic sketch of Profile 2 and its properties (For legend, see Fig. 1).

Profile 2 (Fig. 2, originally described by Mitsuchi, unpubl.)

Location: Hase, Atsugi City, Kanagawa Prefecture
Topography: level valley bottom between dissected terraces
Parent material: river alluvia containing redeposited andic materials
Land use: paddy field

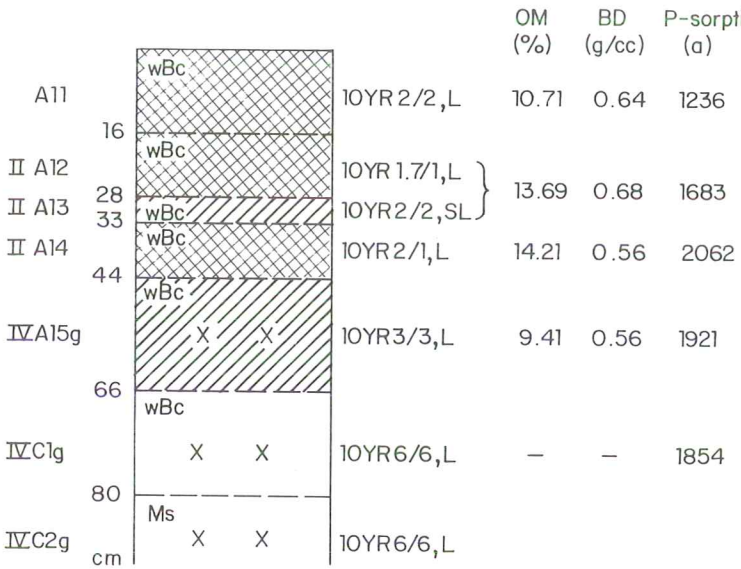
Profile 2 is another example of 1b + 2a. It is similar to Profile 1 in its dark color, low bulk density, and high phosphate sorption capacity throughout the thick profile. But it has a much lower organic matter content and slightly higher color values in the upper part of the profile. Another feature is the presence of orange-colored, thread-like and tubular mottles throughout the profile, although they are less abundant in the surface horizon and the fifth or the lowest horizon. Thus, the aquic soil moisture regime can be easily noted even without the dipyridyl reaction. The lower organic matter content and lower phosphate sorption capacity of this soil would suggest a mixture of nonandic materials in the process of fluvial sedimentation.

Profile 3 (Fig. 3, originally described by Katayama et al [3])

Location: Minamiteshikaga, Teshikaga-cho, Kushiro Subprefecture, Hokkaido
Topography: level floodplain

Parent material: aeolian ashes on river alluvia dominated by redeposited andic materials
Land use: pasture

Profile 3 is a representative of the 1a/1b + 2a pattern. It is characterized by the occurrence of several distinctive aeolian ash layers in the upper part of the profile on top of river alluvia. The A1 horizon or surface 16-cm layer is developed on Meakan -- a volcanic ash that fell twice about 140 and 200 years ago.[1] The next two horizons, IIA12 and IIA13, originated from Kamuinupuri-2a ash of about 500 years ago. The IIIA14 horizon is derived from Kamuinupuri-c and -d ashes that fell about 750-1,150 years ago. The horizons below are river alluvia with Fe mottles. The organic matter content is >10% for the aeolian ash layers, and that of the river alluvia is also very high. Bulk densities are low throughout the profile, irrespective of aeolian or fluvial sediments. Phosphate sorption capacity exceeds 1,500 mg P_2O_5/100 g, which is a threshold value for identifying andic nature in the Japanese standard method, except for the A1 horizon derived from the youngest ash. All the horizons below A1 are supposed to satisfy the requirements of andic material, while the A1 would qualify as vitric material. An aquic moisture regime is obvious for the subsoils with iron mottles.



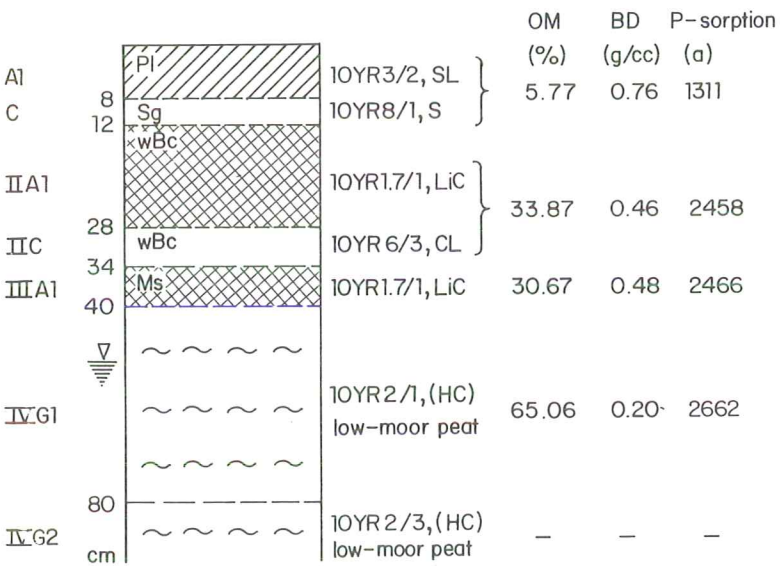
3. Schematic sketch of Profile 3 and its properties (For legend, see Fig. 1).

[1] The data for dating of volcanic ash layers are cited from Sasaki (9).

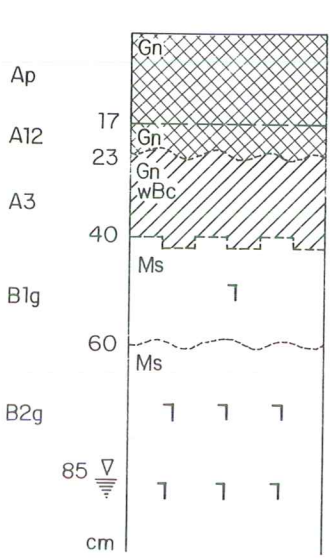
Profile 4 (Fig. 4, originally described by Katayama et al [3])

Location: Nakaonbetsu, Onbetsu-cho, Kushiro Sub-prefecture, Hokkaido
Topography: bog plain
Parent material: aeolian ashes and redeposited andic materials on low moor peat
Land use: grazing land

Profile 4 is an example of the 1a/2b + 2a type. This soil, like Profile 3, has Meakan-a ash at the surface (Al, C), which is underlain by a Yausubetsu ash layer (IIAl, IIC) of about 2,300 years ago. Below these aeolian ash layers occurs a thin river alluvium (IIIAl) that is, in turn, underlain by thick low moor peat beds. Extremely high organic matter contents for the Yausubetsu ash layer and the river alluvium and their occurrence immediately above a peat layer would qualify them as organic soil material, but at the same time these ash and alluvial layers possess high phosphate sorption capacities, except the surface layer of the recent ash. The latter, however, would also satisfy the requirements of vitric soil properties. Should this be the case, the thickness requirement for an Andisol is satisfied. The aquic moisture regime is obvious from the peat formation, but the mere appearance of the ash and the river alluvium does not show it, having neither mottles nor a gray color.



4. Schematic sketch of Profile 4 and its properties (For legend, see Fig. 1).



		OM (%)	BD (g/cc)	P-sorption (b)
Ap	10YR2/1,CL	10.4	0.72	2180
A12	10YR1/1,CL	10.1	0.74	2440
A3	10YR3/2,LiC	6.3	0.55	2500
B1g	10YR4/4,LiC	1.9	0.59	2610
B2g	10YR4/5,LiC	1.8	0.60	2800

5. Schematic sketch of Profile 5 and its properties (For legend, see Fig. 1).

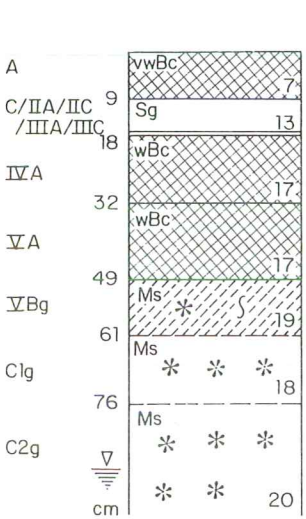
Profile 5 (Fig. 5, originally described by Kubota [5])

Location: Shobunuma, Funaki, Hokota-cho, Ibaraki Prefecture
Topography: depressional part of undulating Pleistocene terrace
Parent material aeolian ash on old alluvia
Land use: upland field

Profile 5 is an example of the 1a + 2b type. The surface 40 cm of this high organic matter content soil is presumably derived from old ash falls from the Haruna-Akagi volcanoes in the northern Kanto district. The yellowish-brown subsoils are massive and show signs of wetness in the form of filmy mottles. The groundwater level was at 85 cm from the surface at field description. The entire profile has low bulk density and high phosphate sorption capacity and appears to be andic in nature. It should be noted that the B1g and B2g horizons have high chroma in spite of their wetness. As the subsoil color chroma of the nearby nonwet soils is known to range from 6 to 8, a relative lowering of chroma caused by wetness is evident, but the absolute chroma of wet andic subsoils is often misleadingly high.

Profile 6 (Fig. 6, originally described by Otowa and Saigusa, 1983, unpubl.)

Location: Kitamotoimatsu, Obihiro City, Tokachi Subprefecture, Hokkaido



	OM (%)	BD (g/cc)	P-sorption (BM)	Acid oxalate sol. Al (%)
10YR1.7/1,L	18.6	0.53	69.2	0.72
10YR4/6-7/2.5-5/5, (stratified) SL/S	3.8	0.82	48.7	0.48
10YR1.7/1,CL	25.9	0.40	97.7	3.02
10YR1.7/1,CL~LiC	22.2	0.35	98.2	6.43
10YR~2.5Y5/3,CL	11.8	0.39	97.9	7.90
2.5Y6/3,CL	8.2	0.40	97.2	5.92
5Y7/2,CL	0.5	–	35.3	0.42

6. Schematic sketch of Profile 6 and its properties (For legend, see Fig. 1).

Topography: depressional part of Pleistocene terrace
Parent material: aeolian ash on old alluvia
Land use: secondary deciduous forest (*Fraxinus mandsheerica* Rupr., *Alnus japonica* Steud.)

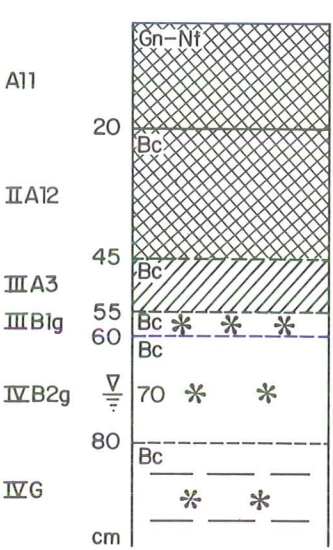
Profile 6 is another example of the 1a + 2b type. The surface 18 cm of this profile consist of a few aeolian ash layers, Meakan-1a (about 140 years ago), Meakan-2a (about 200 years ago), and Tokachi-b (about 200 years ago). These recent ashes are underlain by Tokachi-c1 (about 2,000 years ago) and Tokachi-c2 (about 3,200 years ago) with black color and high humus content. The horizons below VA (Tokachi-c2) are massive and impervious and have many Fe mottles, but their chroma remains relatively high at 3, except the lowermost white clay. The results of laboratory analyses indicate that the horizons between the surface and the white clay are all andic, having low bulk density, high phosphate sorption capacity, and high enough acid oxalate soluble Al. Of the recent ashes, even the sandy-textured Tokachi-b qualifies as a vitric material, having a slightly higher oxalate soluble Al than required.

Profile 7 (Fig. 7, originally described by Kato [4])

Location: Shichiguri, Hisai City, Mie Prefecture
Topography: level part of Pleistocene terrace
Parent material: old alluvia
Land use: mixed pine and deciduous tree stand

Profile 7 is an example of the so-called "non-volcanogenous" ando soils in Japan. These ando soils or kuroboku occur on middle or low terraces with level-surface topography; have few or no volcanogenous particles such as pumice, scoria, and volcanic glass; and often accompany compact, heavy-textured subsoils with more or less wet characteristics. This profile may represent the wettest members of this type of soils. Black surface horizons are characterized by a very high organic matter content and also a high phosphate sorption capacity. Bulk density data are not available, but from the very high organic matter content we can assume that at least those of the surface horizons would be well below the requirement of andic materials. Thus, the soil qualifies as an Andisol. Aquic characteristics are seen from the horizons immediately below the epipedon as many orange-colored Fe mottles.

One of the specific features of Profile 7, compared with the other Andisol profiles quoted herein, is the dominance of crystalline minerals in its clay mineral composition. The main part of the phosphate sorption capacity, therefore, is attributable to hydroxy Al polymers bound to organic matter. This is shown by the low P1-P0 ratios for the humus-rich horizons. P1 is the phosphate sorption measured after peroxide treatment of the soil and P0 is that measured before the treatment. The P1-P0 ratio remains 1 or higher for Andisols dominated by amorphous clays.



		OM (%)	P-sorption (b)	P1:P0 (b)	Exch.acid. Y_1(ml)
AII	5YR1/1,CL	20.2	2340	0.40	36.7
IIA12	5YR1/1,LiC	26.0	3900	0.61	18.2
IIIA3	5YR2/2,LiC	6.6	1860	1.20	17.9
IIIB1g	very dark CL	—	—	—	—
IVB2g	5YR ~7.5YR4/2,HC	4.0	1460	1.31	22.2
IVG	10YR7/1,HC	1.0	340	1.00	48.3

7. Schematic sketch of Profile 7 and its properties. P1 = phosphate sorption measured after peroxide treatment of the soil, P0 = phosphate sorption measured before the treatment (For legend, see Fig. 1).

The type of Profile 7 is difficult to identify. As this type of soil is often found in a relative depression on a terrace surface, redeposition of the surface material is a likely mechanism, i.e., 1b + 2b. But the possibility of the 1a + 2b type cannot be ruled out for this type of kuroboku soil. Should this be the case, the assumption of "nonvolcanogenous" origin totally fails and the soil should be called a "nonallophanic" ando soil, the occurrence of which is now fairly well established in Japan.

CLASSIFICATION OF WET ANDISOLS WITH AN AQUIC MOISTURE REGIME

The proposed classification scheme for Andisols first keys out Aquands on the basis of the following characteristics (2):

A Andisols that have an aquic moisture regime or artificial drainage and have one or more of the following:
- (a) A histic epipedon.
- (b) At a depth of less than 50 cm or immediately below an epipedon that has color values, of 3 or less, dominant colors, moist, on ped faces or in the matrix, if peds are absent, as follows:
  - (1) If there is mottling, chroma of 2 or less.
  - (2) If there is no mottling, chroma of 1 or less.
- (c) A placic horizon that rests on a duripan.
- (d) Where there are melanic properties[2] throughout the upper meter, sufficient active Fe^{2+} to give a positive α,α'-dipyridyl reaction within 50 cm of the surface at some time of the year.

Further, the proposed key to great groups reads as follows:

AA	Aquands that have an isohyperthermic temperature regime.	TROPAQUANDS
AB	Aquands that have a duripan.	DURIAQUANDS
AC	Aquands that have vitric soil properties beginning at or within 25 cm of the surface and extending throughout a continuous thickness of 35 cm or more.	VITRAQUANDS
AD	Aquands that have an epipedon 30 cm thick or thicker with color values, moist, of 2 or less and chromas of less than 2 throughout, or have a subsurface buried horizon that meets these requirements, is	

[2] Melanic properties are those conditions of color and organic C used to define melanic great groups.

30 cm or more thick, and has its upper surface within 1 m of the soil surface; and have 8% or more organic carbon as a weighted average throughout these thicknesses. MELANAQUANDS

AE Other Aquands. HAPLAQUANDS

Classification of the sample profiles

The profiles discussed in the preceding section are classified according to the proposed scheme, as follows:

Profile 1 is classified as a Melanaquand because of its high organic matter content, its thick profile with low chroma and value, and its positive dipyridyl reaction within 50 cm of the surface.

Profile 2 should be classified as an Aquand from its appearance with Fe mottles throughout the profile, but mottles alone cannot place it in the Aquand suborder. We understand that criterion (b) for Aquands is meant to be applied only to nonhumiferous horizons. Moreover, the relatively low organic C content of the soil does not allow the application of criterion (d) for the soils with melanic properties, or the use of the dipyridyl test. Although we feel it totally inappropriate, Profile 2 is classified only as an aquic subgroup of, most probably, the Hapludands in the present scheme.

Profile 3 does not qualify as an Aquand because the chroma of the horizon with aquic features within 50 cm of the surface or that immediately below an epipedon with color value of 3 is too high, although Fe mottles are present. Thus, this soil may be classified as an aquic subgroup of other Andisols. The soil temperature regime suggests that the soil belongs to the Aquic Haploborand.

Profile 4 is keyed out as a Histosol according to the present key to the orders, for the soil layers below 12 cm of the surface contain organic soil materials, in spite of the fact that the surface 40 cm of the profile also satisfies the requirements of an Andisol. Therefore, the soil is classified as an Andic subgroup of a Borohemist.

Profile 5 is constituted of andic materials throughout, but its aquic feature is

not expressed clearly within 50 cm of the surface. The chroma is too high for the horizon immediately below the epipedon in spite of the occurrence of Fe mottles. Thus, it is not classified as an Aquand, but probably as an Aquic Hapludand.

Profile 6 is similar to the preceding profile. The horizon immediately below the epipedon has too high a chroma to be classified as an Aquand. But an aquic feature is evident in the many distinct mottles. Thus, this soil may be classified again as an Aquic Hapludand.

Profile 7 may be another Aquand if we take the chroma of the IVB2g horizon as the dominant color of a horizon immediately below the epipedon. Because of the very black color and the very high organic C content of the A11 and IIA12 horizons, the soil is classified as a Melanaquand. Probably a subgroup separation would be necessary to indicate the specific clay mineralogical feature of the soil that is associated with a high exchange acidity (Fig. 7). A tentatively proposed subgroup, "allic," may be applicable to this soil.

Problems relevant to classification of wet Andisols

From the above discussion, a few points relevant to the classification of wet Andisols emerge. One is the color requirement (b) in the proposed key to Aquands, which states that Aquands are the soils that have an aquic moisture regime and either chroma of 2 or less when there is mottling or chroma of 1 or less when there is no mottling, within 50 cm of the surface or immediately below an epipedon with a value of 3 or less.

There are difficulties in applying these criteria to wet Andisols. The black humiferous A horizon of wet Andisols often does not show readily recognizable characteristics associated with wetness, such as gray color and mottles with low chroma, even when it has an aquic moisture regime (cf. Profile 1). Moreover, the black A horizon is often very thick, and if we take the color of a horizon immediately below an epipedon, it may not have any relevance to the moisture regime of the upper 50 cm of the soil. This condition seems to have been taken into consideration when criterion (d) of the proposed key for Aquands was set out for a soil having melanic properties throughout the upper metre.

Even when the black A horizon is thin, andic or vitric subsurface horizons usually do not exhibit a low chroma as required for Aquands, in spite of the presence of mottles (cf. Profile 3, 5, and 6).

These difficulties urge us to adopt a simple field test such as the dipyridyl reaction to detect Fe^{2+} as a product of a reduced condition. And if such a reaction is to be adopted in the case of soils with deep melanic properties (criterion d), it should be adopted in other cases, too, to avoid difficulties in detecting the characteristics associated with wetness.

Another characteristic that should be adopted is the occurrence of distinct to prominent mottles because of Fe segregation, regardless of the chroma of the matrix in the case of andic or vitric materials.

Another point that requires clarification is the distinction between the histic epipedon and the black humiferous epipedon of wet Andisols. The Yausubetsu ash layer and the underlying fluvial deposit of Profile 4 are sufficiently high in organic C relative to their clay content and saturated with water for a long period, and thus qualify as organic soil material. But at the same time they are andic in nature with a high phosphate sorption capacity. There is an important difference between the organic matter contained in ordinary organic soil material saturated with water and that in andic material. Even sapric material, the most humified or decomposed among the organic soil materials, is much less humified than the organic matter in Andisols. The organic matter in Profile 4 has a relatively low C-N ratio of 17 and is associated with active alumina to give a high phosphate sorption capacity, suggesting that it is definitely much more humified than peaty organic materials. Therefore, the classification of Profile 4 as an organic soil (Andic Borohemist) is not quite acceptable. It must be classified as a Haplaquand based on the surface 40 cm of andic and vitric materials.

In the recent proposal for the Andisol classification, there is another point related to the above discussion. According to the proposal, a well-drained soil with a melanic horizon thicker than 40 cm and with 20% or more organic C would be classified as an Andic Histosol. Again, the nature of organic matter in such a soil is entirely different from that in ordinary Histosols. In our opinion, soils with such organic matter should be classified as Andisols because these soils are more similar to other Andisols than to Histosols in fertility characteristics.

Proposed criteria for wet Andisol classification

The following proposals are based on the preceding discussion:

1. Andisols should be keyed out before Histosols.
2. The keys for Aquands must be revised as follows:

A Andisols that have an aquic moisture regime or are artificially drained and have one or more of the following:
(a) A histic epipedon, or nonandic organic soil materials, the upper boundary of which occurs within 50 cm of the surface.
(b) At a depth of less than 50 cm from the surface, one or more of the following characteristics associated with wetness:
(1) distinct to prominent mottles due to Fe segregation.
(2) sufficient active Fe^{2+} to give a positive α,α'-dipyridyl reaction.
(3) color value of 4 or more and chroma of 2 or less immediately below an epipedon.
(c) A placic horizon that rests on a duripan.[3]

"Aquic" subgroups of the other Andisols should be defined as follows: Andisols that have one or more of the following characteristics associated with wetness between 50 cm and 100 cm of the surface,
(1) distinct to prominent mottles due to Fe segregation,
(2) nonandic organic soil material with water saturation,
(3) sufficient active Fe^{2+} to give α,α'-dipyridyl reaction at some time of the year,
(4) color value of 4 or more and chroma of 2 or less.

WET ANDISOLS WITH ANTHRAQUIC MOISTURE REGIME

Dudal and Moormann (1) proposed the adjective "anthraquic" to denote the "inverted gley" phenomenon that appears in the surface plow layer of artificially irrigated paddy soils. The "inverted gley" means not only surface gleyzation due to submergence but also the morphological alterations induced by submergence. Major morphological changes are the formation of an illuvial horizon of ferric and manganic oxides due to alternations of the redox condition in the course of rice cultivation.

Andisols on fans, terraces, and footslopes of hills and mountains are widely utilized for rice cultivation in Japan after terracing, leveling, and bunding. Some of them may be aquic subgroups of soils belonging to Udands and Allands, but most are freely draining nonaquic soils. Repeated plowing and puddling under water facilitate formation of a plow sole, with which submergence in water during the rice-growing season becomes easy. Such an artificial submergence

[3] The importance of this criterion is not known to us. This has been simply inherited from the tentative proposal for Icomand.

with irrigation water and all the induced changes therefrom in a moisture regime may be called an "anthraquic" moisture regime, after Dudal and Moormann.

The characteristics of a wet Andisol with an anthraquic moisture regime can best be understood when such a soil is compared with an adjacent soil without any drastic artificial modifications. Two such comparisons follow.

Profile description

Example 1 is taken from Tottori Prefecture and Example 2 from Nagano Prefecture. Paddy soil profiles (P) and upland soil profiles (U) are illustrated schematically in Figures 8 and 9 for Examples 1 and 2 (7).

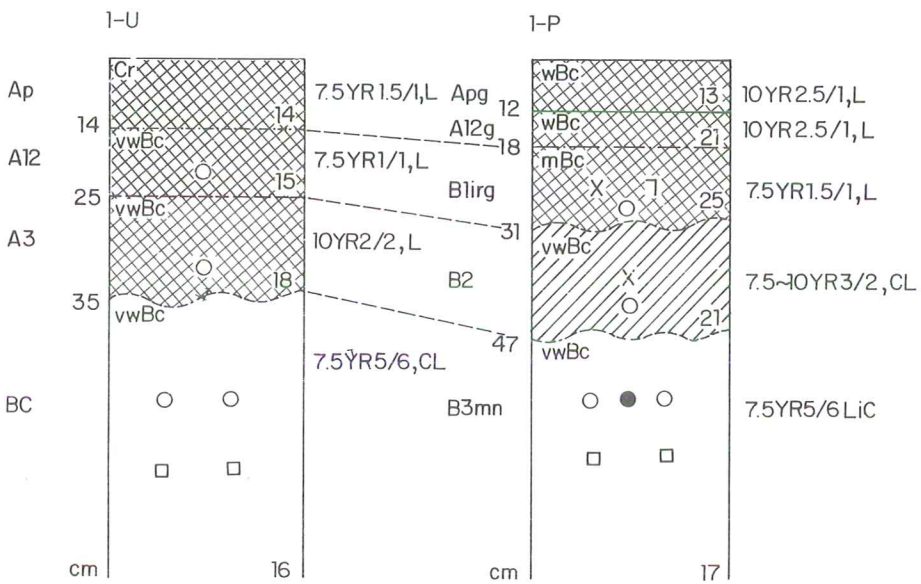
Example 1

Location: Kanayadani, Mizoguchi-cho, Tottori Prefecture

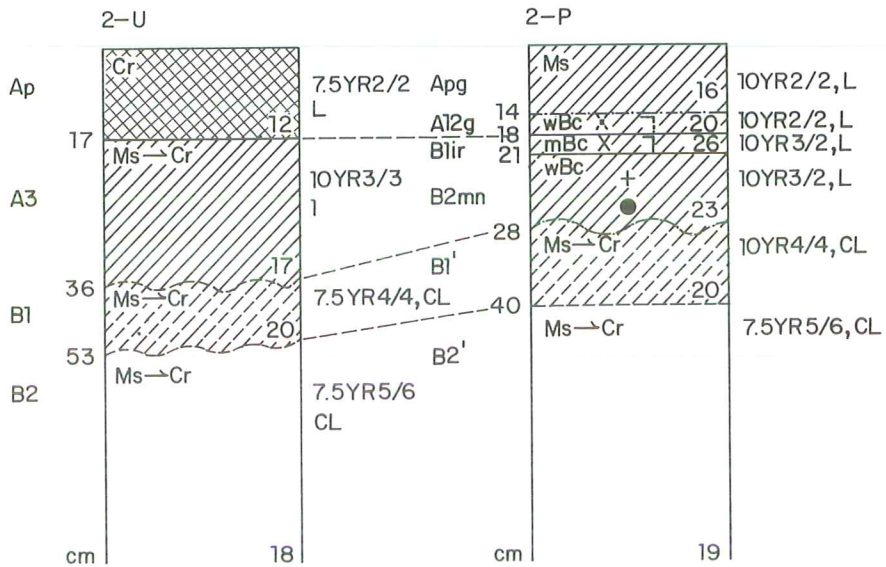
Topography: western footslope of Mt. Daisen (resting volcano), sloping toward west 7%; elevation 280 m MSL

Parent material: andesitic volcanic ash originating from Daisen (somewhat mixed with fine pumices) which erupted 4,800 years ago and 2,500 years ago according to ^{14}C dating

Climate: mean annual temperature 14.5°C; mean annual precipitation 2,036 mm



8. Comparison of morphological features between two profiles of an Andisol in Tottori Prefecture (Example 1) under paddy (1-P) and upland (1-U) crops (For legend, see Fig. 1).



9. Comparison of morphological features between two profiles of an Andisol in Nagano Prefecture (Example 2) under paddy (2-P) and upland (2-U) crops (For legend, see Fig. 1).

Example 2

Location: Shimohara, Hata-cho, Nagano Prefecture
Topography: dissected fan, sloping toward east 2%; elevation 670 dm MSL
Parent material: ash from volcano that erupted about 20,000 years ago
Climate: mean annual temperature 11.0°C; mean annual precipitation 1,063 mm

In Example 1, the two profiles are 10 m apart. Profile 1-P has been used for rice cultivation for about 50 years, once every year, while 1-U has been used for upland crops such as sugarcane and vegetables. Profile 2-P has been under rice continuously for at least 60 years. It is about 80 m apart from 2-U, an ordinary upland field. Thus, we can assume that whatever differences are detectable between the two profiles in these two cases have been brought about by the management practices in rice cultivation.

Morphological characteristics

In common to both the paddy soil profiles, basic Andisol characteristics are still well preserved, such as a thick, very dark surface layer and bright brown subsoil layers. At the same time rice cultivation causes such morphological changes as the following:

- The Apg horizon of the paddy soils has a slightly lessened reddish hue and also a slightly increased color value.

- Iron and Mn illuvial horizons have been formed separately in the paddy soil profiles. In I-P, Mn is translocated quite far down from the place of origin. The movement of Fe and Mn will be discussed later in more detail.
- The subsurface layers in the paddy soil profiles have been compacted as a result of plowing and puddling and also partly because of Fe illuviation.
- The crumb structure, which is characteristic of Andisols, has been destroyed in the Ap horizon of the paddy soils. Furthermore, a moderately developed blocky structure has been formed in the plow sole.

Physical, chemical, and mineralogical characteristics

As shown in Table 1, the most conspicuous characteristics of Andisols, such as a very high organic matter content, a very high phosphate sorption capacity, and a low bulk density, are preserved. But, at the same time, there is a slight decrease in organic matter in the surface layer, an accompanying decrease in cation exchange capacity in the surface layer, and an increase in exchangeable Ca and in the percentage base saturation in the surface layer of paddy soil. Furthermore, the degree of humification of humic acids is lowered in

Table 1. Chemical and physical characteristics of "anthraquic" Andisols in comparison with their nonanthraquic counterparts.

Soil	Horizon	OM (%)	BD (g/cc)	P-sorption (a) (mg/100 g)	Exchangeable			Humic acid		Hydraulic conductivity (cm/s)
					CEC (meq/100 g)	Ca	PBS (%)	(−log K)	(RF)	
I-P	Apg (A11)	18.5	0.51	1940	36.6	8.69	28.7	0.528	118	–
	A12g (A11)	17.6	0.71	1990	35.0	7.12	24.4	0.525	131	–
	B1irg (A12)	18.0	0.68	2190	37.1	5.38	18.0	0.512	147	–
	B2 (A3)	9.9	0.58	2170	–	–	–	0.528	131	–
	B3mn (BC)	1.4	0.78	1340	11.8	3.55	44.9	0.660	69	–
I-U	Ap	18.6	0.58	2185	39.1	7.81	24.8	0.518	141	–
	A12	18.9	0.50	2430	37.2	3.46	10.8	0.507	152	–
	A3	11.2	0.57	2420	–	–	–	0.514	144	–
	BC	1.6	0.78	1340	11.4	4.75	48.3	0.637	77	–
II-P	Apg (A1)	10.3	0.79	1660	21.2	7.77	42.1	0.528	106	1.5×10^{-3}
	A12g (A1)	9.8	0.90	1710	21.7	7.59	39.1	0.524	111	1.1×10^{-5}
	B1ir (A3)	7.0		1890	17.6	6.86	44.7	0.538	110	
	B2mn (A3)	5.8	0.67	1920	12.7	4.49	41.5	0.532	114	1.7×10^{-3}
	B1′	3.5	0.76	1690	12.9	4.62	42.6	–	–	1.0×10^{-3}
	B2′	2.0	0.65	1830	11.6	3.55	38.3	–	–	1.0×10^{-3}
II-U	Ap	12.4	0.66	1880	27.2	6.67	27.9	0.519	117	2.9×10^{-2}
	A3	6.3	0.62	2317	16.8	2.14	16.4	0.515	121	4.8×10^{-3}
	B1	2.7	0.69	1840	12.3	5.50	51.9	–	–	3.4×10^{-3}
	B2	1.9	0.75	2000	11.8	5.00	46.7	–	–	1.1×10^{-3}

the surface soil, as judged from such indices as log K and RF.[4]

Although bulk densities are still maintained generally low, the subsurface layer of paddy soils has undergone a slight compaction as a result of both plow sole formation and Fe illuviation. This is also seen in the decrease in hydraulic conductivity by two orders in the case of Profile 2. This is an essential requisite of paddy soils of Andisol origin; otherwise water consumption would be too large.

X-ray diffraction and differential thermal analysis revealed that allophane, vermiculite, chlorite, illite, and gibbsite are the common constituents of the clay fraction of both the sites. Except for an increase in gibbsite toward the subsoil, there is no conspicuous difference vertically. Rice cultivation for 50-60 years does not seem to have affected clay mineralogy significantly. The only detectable change is a slight increase of gibbsite in the surface horizons of paddy soils. Changes in the amorphous fraction, if any, would not be very conspicuous.

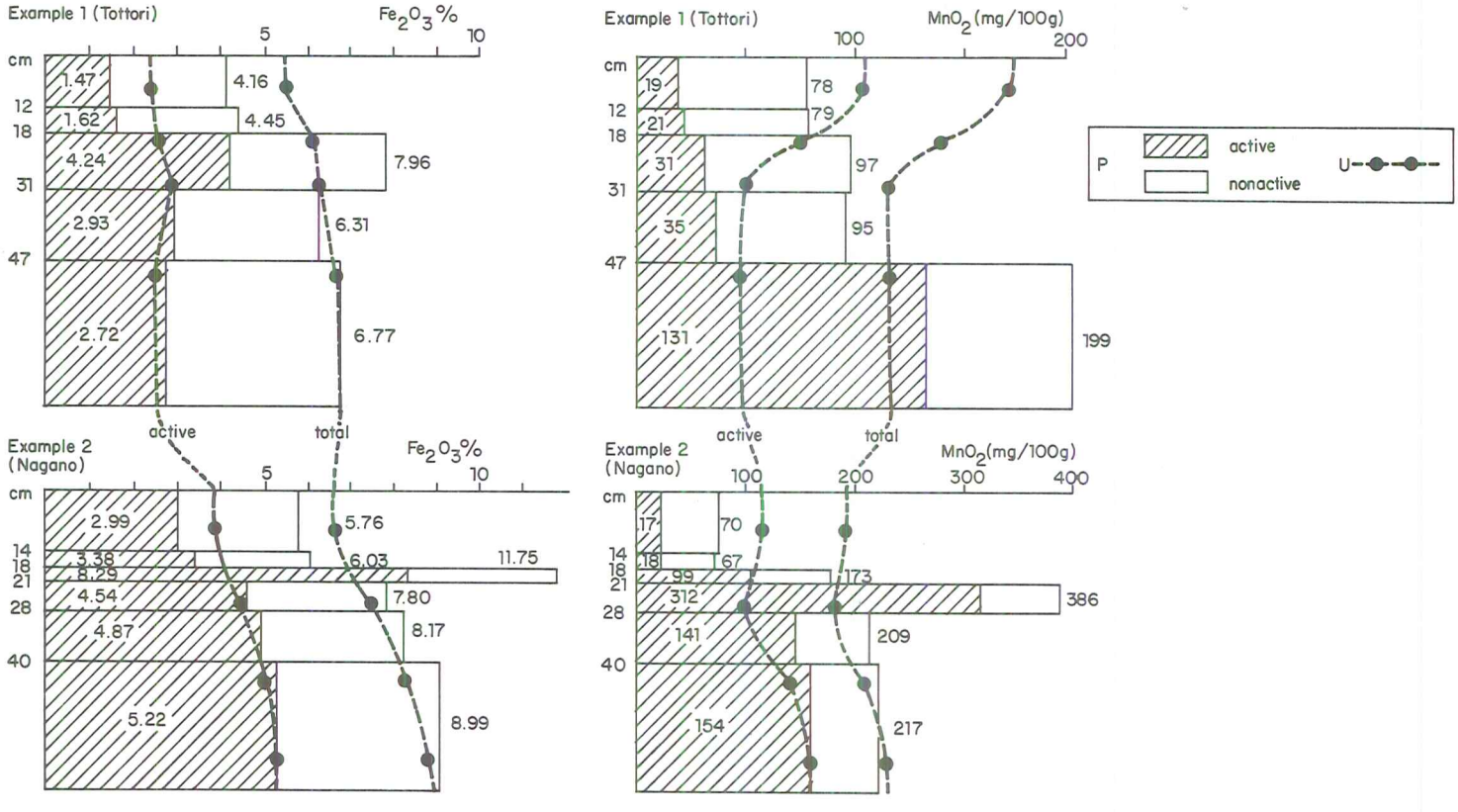
Eluviation-illuviation of iron and manganese

Figure 10 illustrates the distribution of total as well as active (extractable by Mg-ribbon reduction method) Fe and Mn oxides. Eluviation of total and active Fe from the Apg and A12g horizons and their illuviation in the B1irg horizon are obvious in both the 1-P and 2-P profiles. If we regard the Fe content in the upland soil profile as the original content of the paddy soil profile, 40% of the active Fe_2O_3 in Apg was lost in 1-P and 22% in 2-P. All the Fe lost appeared precipitated in B1irg; thus almost no changes are detectable in the horizons below.

In the case of Mn, as much as 80% of the active content was lost from the Apg and A12g horizons. It was lost even from B1irg and B2 and precipitated very conspicuously in B3mn in the 1-P profile, whereas Mn illuviation occurred immediately below the Fe illuvial horizon in 2-P.

A stated here, eluviation and illuviation of Fe and Mn oxides are no less conspicuous in Andisols than in other soils when they are used in rice cultivation for a considerable period. There is, however, one specific feature of Andisols. Illuviated Fe and Mn oxides in nonandic soils form distinct to prominent mottles of fine tubular or thread-like, filmy, or spotty shape. In Andisols, the occurrence of these mottles is rare relative to the amount of these oxides illuviated. The paucity of mottles in paddy soils of

[4] Both are indices of the degree of humification of humic acids of soil organic matter, proposed by Kumada et al (6). Using these indices Kumada classified humic acids into A, B, P, and Rp types. Humic acids of Andisols are characteristically classified as A type or most humified.



10. Distribution of total as well as active iron and manganese oxides in the Andisol profiles under different land use.

Andisol origin is well documented and is sometimes ascribed to weakness of eluvial-illuvial processes. Obviously this is not true. Closer examination of illuvial horizons shows a diffused precipitation of oxides throughout a wide surface area of porous peds characteristic of Andisols.

In the Apg horizon of both 1-P and 2-P, no mottles were detected. As shown in Figure 10, both soils contain a considerable amount of active Fe; thus it is not right to ascribe the paucity of mottles to the paucity of Fe. Mitsuchi (7) suggested that it might be due to a rapid oxidation of Fe^{2+} after draining of the surface water; a very rapid oxidation does not allow Fe^{2+} to concentrate by diffusion to form a mottle.

Effect of reduction processes on the soil color

Examination of soil color of the Apg horizon after removal of organic matter by repeated peroxide treatments reveals that prolonged use of Andisols for rice cultivation affects the color hue and chroma only slightly. In the case of the two mentioned soils, the hue remained in the range of 7.5-10 YR and the chroma, when moist, was always 3 or higher. The color hue of nonandic soils normally turns to the Y to the GY region and the chroma to lower than 3 after their long-term utilization for rice cultivation. This peculiar coloring behavior of Andisols raises another difficulty in detecting the characteristics associated with wetness, along with the paucity of mottles.

ANTHRAQUIC SUBGROUPS

As is evident from the foregoing descriptions and discussion, an anthraquic moisture regime produces a very specific morphological characteristic that may be considered in classifying soils at a relatively high categoric level. Tentatively, the "subgroup" level is considered appropriate by many people working on paddy soils to deal with the morphological changes induced by an anthraquic moisture regime. But before an "anthraquic" subgroup can be set up, morphological characteristics must be defined more clearly in quantitative terms.

First, it should be noted that anthraquic subgroups are to be recognized in nonaquic soils. Soils of aquic suborders and Histosols would not undergo any noticeable morphological changes because of artificial submergence. However, aquic subgroups would be morphologically affected by wetness in the deep subsoils. Therefore, there could be "anthraquic aquic" subgroups.

Among the morphological changes induced by an anthraquic moisture regime, reductive eluviation and oxidative illuviation of Fe in the surface horizon and Mn in the subsurface horizon are most well expressed. The eluvial process under seasonal gleyzation leaves a grayish matrix color in the surface soil, while the illuvial process is exhibited by the presence of many mottles of Fe and Mn that are thread-like (along fine root channels), tubular (along coarse root or faunal channels), spotty (dense concentration with sharp boundary), or filmy (along cleavage planes or ped faces).

Often reflecting the difference in electric potentials at which Fe and Mn undergo reduction (or mobilization) and oxidation (or immobilization), Fe is deposited more readily immediately below the submerged zone, while Mn is precipitated in lower subsoils. Another explanation for the differentiation of Fe and Mn illuvial horizons is that Mn, which is mobilized more readily than Fe, is first precipitated just below the submerged zone, but later displaced further downwards by Fe^{2+}, which acts as a reducing agent for precipitated Mn.

For the eluvial and illuvial processes of Fe and Mn, permeability of the soil profile is one of the most important factors. According to Mitsuchi (8), highly permeable profiles developed on either lighter-textured or loosely packed brown lowland soils (Fluvents), or both, have more developed Fe and Mn illuviation horizons, which seem to retain all the eluviated Fe and Mn from the seasonally submerged surface layer. Furthermore, under such conditions, the subsoils below the plow sole are kept aerobic and retain the original, brown-colored matrix. The above-quoted anthraquic Andisols are of this type.

On the contrary, in slowly permeable profiles derived from either finer-textured or closely packed brown lowland soils, or both, the gray matrix color extends from the surface down to more than 50 cm or even to nearly 1 m. The subsoils have low-chroma mottles spreading along ped faces and channels and cloud-like Fe mottles (thin concentration with diffuse boundary) in the gray matrix. Mitsuchi (8) attributed the formation of such a subsoil to a loss of Fe along ped faces and channel walls by reductive eluviation as well as to *in situ* segregation of Fe in the matrix, and referred to it as a "pseudogleyed" horizon.

Illuviation of Fe and Mn in the slowly permeable profiles commonly occurs in the transitional zone between the gleyed surface soil and the pseudogleyed subsoils. As a reflection of the forming process of the pseudogleyed subsoil, Fe and Mn accumulation is not as marked as in highly permeable profiles or sometimes is even undiscernible by mere appearance. This is because

the accumulation is only relative; that is, the accumulation is partly offset by a loss from the pseudogleyed subsoils. Analytical results of such a profile in comparison with those of unsubmerged or nonanthraquic profiles in the vicinity clearly show the above effect.

Mitsuchi's pseudogleyed horizon appears to be equivalent to that called a "perco-submergic" horizon by Chinese soil scientists (10), who made an extensive study of paddy soils in the Tai-hu region, where fine-textured soils are widely distributed.

Thus, the presence of the illuvial horizon of Fe and Mn (irrespective of whether they occur together or separately) or the pseudogleyed horizon, or both, may be regarded as the characteristic associated with an anthraquic moisture regime. There are, however, difficulties in recognizing these characteristics. In relation to the illuvial Fe and Mn horizons, it is not always easy to distinguish the mottles of *in situ* segregation from those of illuviation. Furthermore, the distribution of Fe and Mn along a profile is determined by superposition of an eluvial-illuvial process operating on the distribution of these elements in the original sediments.

There is no difficulty in recognizing a pseudogleyed horizon occurring in a nonaquic soil as a characteristic associated with an anthraquic moisture regime. But in the case of soils belonging to aquic subgroups, the pseudogleying of subsurface horizons by artificial irrigation would result in a continuum of aquic characteristics throughout a profile and make the effect of the anthraquic moisture regime obscure. Moreover, it is well known that the groundwater level is raised by artificial irrigation in rice-growing lowlands. Therefore, it would become even more difficult to recognize the irrigation-induced pseudogleying.

PROPOSED CRITERIA FOR ANTHRAQUIC SUBGROUPS

Our tentative proposal of criteria for recognizing an anthraquic subgroup is as follows:
Either or both of the following requirements must be satisfied:

- Clear differentiation of reductive eluviation horizon and oxidative illuviation horizon(s), as evidenced by the following:
  1. There must be a subsurface horizon that is apparently most abundant in mottles with a high chroma due to Fe segregation and contains the highest amount of dithionite soluble Fe in the profile, which is at least twice that of the surface horizon, and

2. One or more of the following are present:
   a. a surface horizon that has a color value of 4 or more and a chroma of 2 or less,
   b. Mn illuvial horizon that contains four times or more of the dithionite soluble Mn than that of the surface horizon, and
   c. uniformly distributed dithionite-soluble Al throughout the profile.

[Note: It may be better to use ratios of dithionite-soluble elements to clay contents rather than dithionite-soluble elements themselves.]

- Irrigation-induced pseudogleyed horizon that extends from immediately below the surface horizon to below 50 cm from the surface, as evidenced by all of the following:
  1. Matrix has a color value of 4 or more and a chroma of 2 or less and is dominated by cloudy mottles (coarse tubular as well as filmy mottles must be few, if any).
  2. Blocky or prismatic structure is moderately to strongly developed when the texture is loamy or finer.
  3. Ped face and pore walls are gray colored (value ≥ 4 and chroma ≤ 2).
  4. n-value <0.7, or bulk density >1.2 or solid volume >45%.

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WET ARIDISOLS

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It is possible that many of the soil series in the U.S. that are classified in aquic subgroups of Aridisols really have an aquic soil moisture regime. They are misclassified because the limited data available when they were classified indicated an aridic regime. Additional data on water tables and moisture regimes in representative soils are needed, however, to support any potential changes that might be made in either classification of soil series or criteria in Soil Taxonomy. Salorthids can have any soil moisture regime, and it does not seem critical that they be restricted to any specified regime.

The title of this paper is a contradiction in terms to highlight an interesting problem in the U.S. Soil taxonomy (2). Considered here are soils that have been classified in the aquic subgroups of Aridisols and the Salorthids. The problems are how best to define the moisture regime in these kinds of soils and to determine whether they exclusively fit one or another of the moisture regimes defined and used in Soil taxonomy. We found no hard data on water tables or moisture regimes for these soils, either through a literature search or through personal inquiries, which means that their classification has been estimated by implication or association.

ARIDISOLS

Aridisols constitute one of the 10 soil orders in the system of classification published in Soil taxonomy. The main property differentiating Aridisols from the other orders is soil moisture content, which is usually too low to support rainfed agriculture other than range and a few specialty crops. Aridisols are characterized by 1) an aridic moisture regime as defined in Soil taxonomy, and 2) one or more diagnostic subsurface horizons.

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The aridic moisture regime requires that the soil moisture control section is 1) dry in all parts more than half the time in most years when the soil temperature at a 50-cm depth is more than 5°C, and 2) never moist in some or all parts for as long as 90 consecutive days when the soil temperature at 50-cm depth is above 8°C. The upper boundary of the soil-moisture control section is the depth to which a dry soil will be moistened by 2.5 cm of water within 24 hours. The lower boundary is the depth to which a dry soil will be moistened by 7.5 cm of water within 48 h.

The soil moisture control section lies approximately between the 10-cm and 30-cm depths if the particle size class is fine-loamy, coarse-silty, fine-silty, or clayey. It extends approximately from the 20-cm to the 60-cm depth if the particle size class is coarse-loamy, and from the 30-cm to the 90-cm depth if sandy (2).

AQUIC SUBGROUPS OF ARIDISOLS

Seven aquic subgroups of Aridisols are described in Soil taxonomy. By definition, these subgroups must have an aridic moisture regime. They also must be either saturated with water for 90 consecutive days within a depth of 1 m or have specified color characteristics or specific Na adsorption ratios, or both, within a depth of 1 m if there is groundwater within this depth at some time in most years (2, 3).

The following aquic subgroups have been correlated in soil surveys in the United States (1):

Aquic Haplargids (6197 ha)
Aquic Natrargids (39,270 ha)
Aquic Haplic Nadurargids (1294 ha)
Aquic Camborthids (12,358 ha)
Aquic Durorthids (13,870 ha)
Aquentic Durorthids (2978 ha)
Aquic Paleorthids (205 ha)

Overall they are limited in extent. Other subgroups, including more than 25,000 ha of Aquic and Aquic Duric Calciorthids in Nevada (George Staidl, personal communication), have been mapped, but they have not been officially recorded in the mapping unit use file (1).

The official descriptions of soil series classified in these aquic subgroups show a wide variety of characteristics for moisture regime. Some examples follow:

- Ausmus series (fine, montmorillonitic, frigid Aquic Natrargids). The soils in this series occur in lake basin areas of south central Oregon and are poorly drained. The soil temperature is more than 5°C from May through November. The soil is dry between depths of 10.0 cm and 30.5 cm from July through October and has a

high water table from the surface to a depth of about 1 m from March through June.

- Duffer series (fine-silty, carbonatic, mesic Aquic Calciorthids). This series occurs in north central Nevada. In most areas the soils are poorly drained; in areas of stream entrenchment, they are somewhat poorly drained. These soils are saturated between depths of 51 cm and 101.5 cm in the early spring and are usually moist because of capillary moisture from groundwater. The soils are periodically dry in the summer and fall.
- Sombrero series (loamy, mixed, shallow Aquentic Durorthids). This series occurs in north central Nevada. It consists of somewhat poorly drained soils that are saturated at depths of 76 cm to 101.5 cm during the spring in most years.

Typically, the soils in these three series are in drainageways and depressional areas in lake basins; on nearly level floodplains, terraces, and lake plains; and on nearly level remnant stream or lake terraces. These are all positions where water collects and a natural high water table is expected. The mean annual precipitation commonly ranges from 12.5 cm to 28.0 cm.

In the U.S. all the soil series classified as aquic subgroups of the Aridisols are typically described as somewhat poorly drained or poorly drained, or both. These drainage classes are common to soils with an aquic moisture regime, but not to soils with an aridic moisture regime.

The aquic moisture regime is a reducing regime that is virtually free of dissolved O_2 because the soil is saturated by groundwater or by water of the capillary fringe. Besides saturated soil, the environmental conditions must be such that the biological respiration rate is greater than the reoxygenation rate. Soil taxonomy does not specify how long the soil must be saturated for an aquic moisture regime, other than it "must be at least a few days" for respiration processes to deplete the O_2 (2).

Many of these poorly drained and somewhat poorly drained soils in the aquic subgroups of the Aridisols seem to meet the wetness requirements for the aquic soil moisture regime. Data are not available, however, to show whether they have a reducing regime when they are saturated in the spring or early summer.

The reducing regime for these soils is often too short to provide the reducing conditions for Fe, but it is long enough for the reduction of NO_3^-. This condition could be critical to plant growth and should be considered in the use and management of the soil. It is especially important to consider this process as it occurs in flooded rice fields.

If there is rapid and deep draw-down of the water table during spring or early summer, these soils could dry out in the arid climate and meet the dryness requirements for the aridic moisture regime. The question is whether some of these soils meet the requirements of both the aquic and aridic moisture regimes.

No statement in Soil taxonomy implies that the same soil can have two moisture regimes. But if a soil appears to meet the requirements of two classes in the same category, it should be placed in the first listed class, which in this case is the aquic moisture regime.

Additional speculations can be made, but without hard data they may be meaningless. For example, how should these soils be classified if they really lack an aquic moisture regime but do not qualify for an aridic moisture regime designation because of their udic, ustic, or xeric moisture regimes.

SALORTHIDS

Salorthids do not have argillic and natric horizons or a duripan, they have a salic horizon whose upper boundary is within 75 cm of the soil surface. They are saturated with water within a depth of 1 m for 1 mo or more in most years unless artificially drained (2).

The Salorthids appear to be more extensive than all other wet Aridisols combined. For example, at least 58,000 ha have been correlated in Texas alone (Charles M. Thompson, pers. comm.). It has been estimated that all the Salorthids mapped in Texas have an aquic moisture regime.

Except for the requirement that Salorthids must be saturated at the specified depth for the specified duration, the soil moisture regime class is not critical to classification. Salorthids can probably be found to represent all the recognized soil moisture regime classes -- aquic, aridic, udic, ustic, and xeric. The salic horizon in combination with the water table is considered more important than most other soil characteristics for classification or interpretation.

CONCLUSIONS

It is possible that many of the soil series classified in aquic subgroups of the Aridisols really have an aquic soil moisture regime. They are misclassified because the limited data available indicate an aridic regime. Before we make any changes in either classification or criteria, we need additional data on water tables and moisture regimes in representative soils.

Salorthids can have any soil moisture regime, and it does not seem critical that they be restricted to any specified regime.

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REGIONAL STUDIES (JOINT)

WETLAND SOILS IN CHINA

GONG ZI-TONG

In China, wetland soils are defined as those soils subject to submergence and waterlogging and having specific horizons formed under submerged conditions. They are generally called hydromorphic soils and are further subdivided into two suborders: bog soils and anthropogenic hydromorphic (paddy) soils. The bog soils are characterized by a humus (peat) horizon and a gley horizon, while the paddy soils are characterized by their seasonal waterlogged and submerged horizons and a redoxic mottled horizon with alternate oxidation and reduction. Under the bog soil suborder are four great groups: salt-affected, carbonated, siallitic, and allitic soils. Each great group may be subdivided into meadow bog soils, muddy bog soils, humic bog soils, humic-peaty bog soils, peat soils, and other subgroups. Similarly, the paddy soils can be classified into the same four great groups as bog soils, and each great group may be subdivided into four subgroups: oxidic, redoxic, reducing, and leached paddy soils. In addition, there are acid sulfate bog soils and acid sulfate paddy soils in tropical China.

Wetland soils, as far as we comprehend, are just hydromorphic soils. At the beginning of this century the hydromorphic soils were classified by V. V. Dokuchaiev and then by C. F. Marbut as an independent soil type. At present, hydromorphic soils are still used in the FAO-UNESCO Soil map of the world, the Soil map of Europe, the Soil map of Africa, and soil classification systems in many countries such as Canada and Romania. Although the soil classification system of China has been changed several times, hydromorphic soils have been prominent in all the classifications.

Hydrothermal conditions constitute a major factor in the formation of soils. Wetland soils vary greatly because of different conditions of submergence and

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waterlogging induced by groundwater or irrigation water. These soils have their specific genetic horizons, including gley, humus-gley, waterlogged, seasonal submerged horizons, etc., that are formed under submerged or waterlogged conditions. The wetland soils of China have three characteristics:

- a large area, covering about 36 million ha, accounting for 3.8% of the total land area and 11% of the flat land area of the country;
- heavy cultivation, about 70% of these soils being anthropogenic wetland soils, of which some have been developed from nonwetland soils as a result of irrigation, especially in tropical, subtropical, and salt-affected regions; and
- a 7,000-year history of rice cultivation that was revealed when some indica rice grains were excavated from ancient ruins.

China's wetland soils may be categorized into four kinds:

- Bog soils have a high groundwater table, soil pores filled with gravitational water, and a gley horizon extending even up to the soil surface; the soil is in the reduced state throughout the whole profile all year round.
- For groundwater paddy soils, the groundwater table is lowered for planting rice by artificial drainage, the surface water being separated from the groundwater and the gley horizon moving downwards; the surface stratum of the soil alternates seasonally between oxidized and reduced.
- Well-drained paddy soils are derived either from bog soils by draining or from meadow soils by submergence, and are influenced by both groundwater and surface water; however, the irrigation water is not connected with the groundwater, and the gley horizon is at a depth of 1 m or more; below the reduced surface layer is an oxidized layer, under which there is another reduced layer.
- In surface water paddy soils, the surface layer is the only horizon of the soil in the seasonal reduced state due to irrigation and is designated as a waterlogged horizon; oxidation in the waterlogged horizon is also seasonal, and underneath this horizon the soil is still in the oxidized state. After drainage in winter and before rice is planted in spring, almost no difference can be found between this soil and the original soil before rice cultivation.

Because of the complexity of soil-forming conditions, diversity of the parent materials, and variation in degrees of soil development, the range of wetland

soil types in China is wide. Nevertheless, in some influential soil classification systems such as Soil taxonomy (10) there is only the order of Aridisols and no order for hydromorphic soils. The Histosols are classified as a soil order, while hydromorphic soils are considered only as a unit under the order (9).

DISTRIBUTION OF WETLAND SOILS

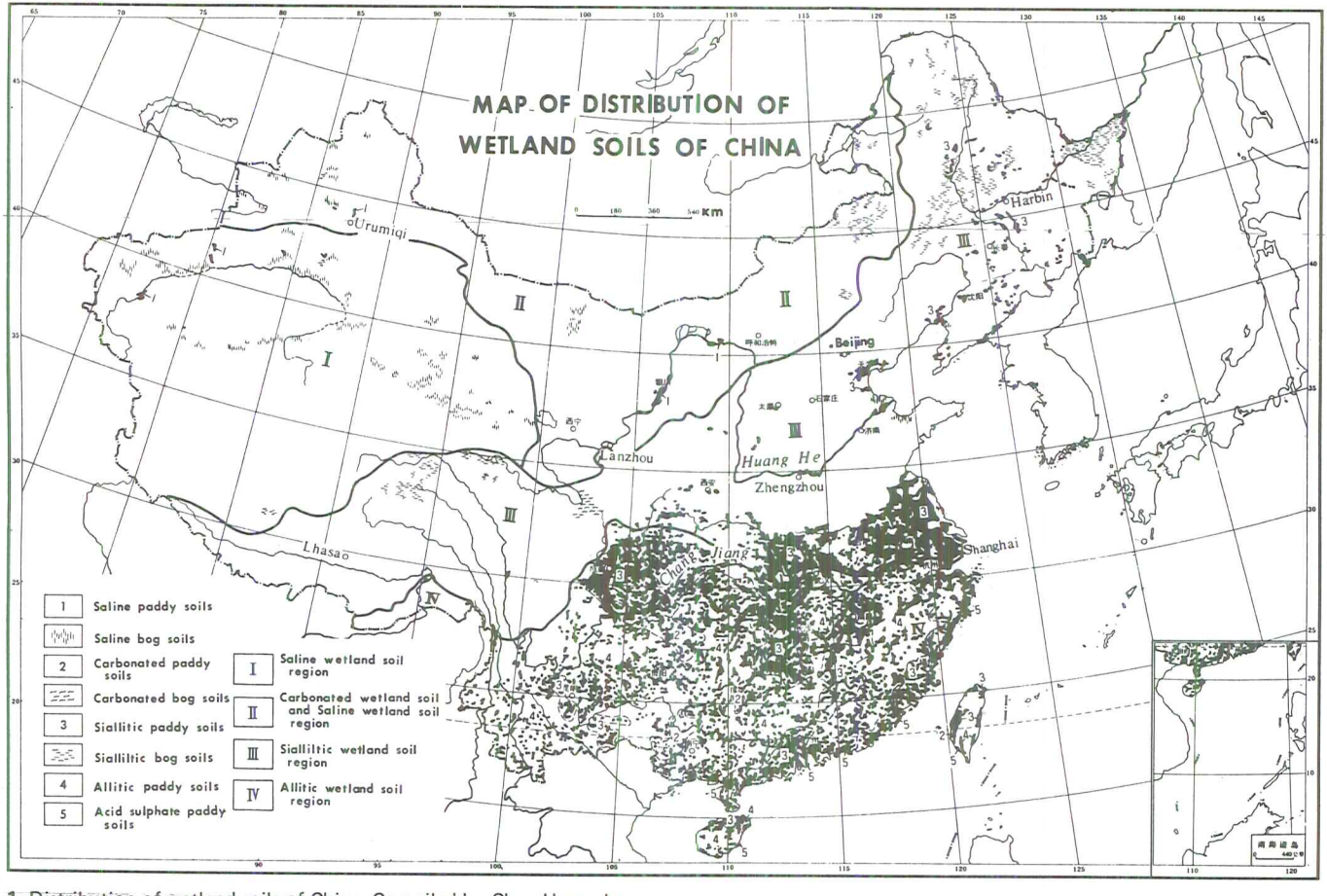
In China, wetland soils are found in almost every region, but the bog soils are distributed mainly in the temperate zone of the northeast and the high mountain plateau regions such as Qinghai, Xizang (Tibet), and Xinjiang, whereas 92% of the paddy soils are distributed south of the Qingling Mountains, the Huai River, and the Bailougjiang River, being especially concentrated in the plain, middle, and lower reaches of the Changjiang River, the Chendu Plain, and the Zhujiang Delta. The wetland soils in China can be divided into four regions according to geochemical characteristics (Fig. 1).

Salt-affected wetland soil region

The salt-affected extremely drought-prone and severely cold region lies in the Talimu Basin, the Chaidamy Basin, and around the lakes of the Xizang Plateau. The annual rainfall in the region is generally <50-100 mm, and the area of wetland soils is limited. Except for some salt-affected paddy soils scattered in Yangi, Akesu, Hetian, and other counties in Xinjiang, few salt-affected paddy soils are found there. The area of salt-affected bog soils is also very small, and the bog rate (bog area as a percentage of total area in a region) of the whole region is only about 0.7%. The bog soils of this region are located chiefly on the fringes of mountain alluvial fan depressions along the rivers and on the beaches of flinched inland lakes or basinal lakes (Fig. 2a) where the water is fed mainly by groundwater and melting ice and snow. With high degrees of salinity these soils generally have efflorescences and salt crusts on the surface of grass domes.

Carbonated wetland soil and salt-affected wetland soil region

The carbonated wetland and salt-affected wetland region, with an arid climate, an annual rainfall of 250-650 mm, and strong evaporation, is located in the steppes of the temperate zone and the desert area of Inner Mongolia and Xinjiang. The extent of wetland soils in this region is about 0.4%. In this region, the paddy soils are mainly in the river basins and the discharge areas of groundwater at the feet of the mountains. The surface of the paddy soil is continuous-

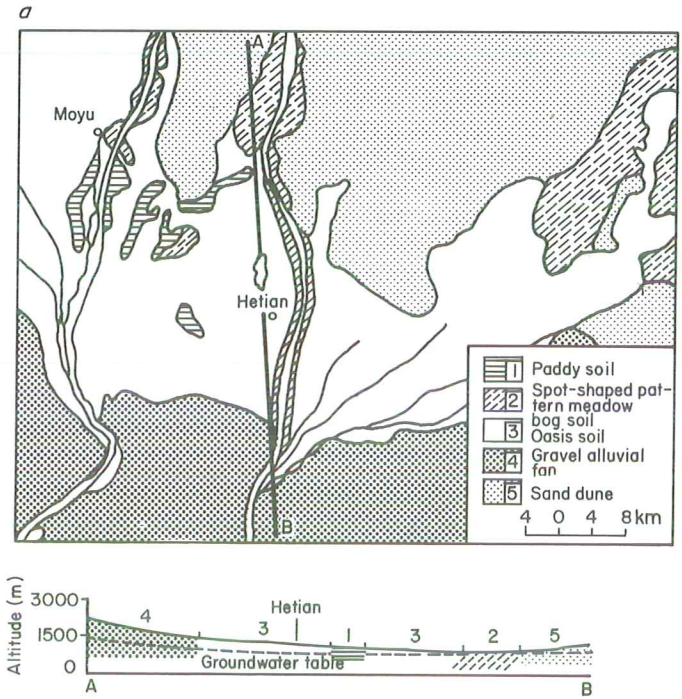


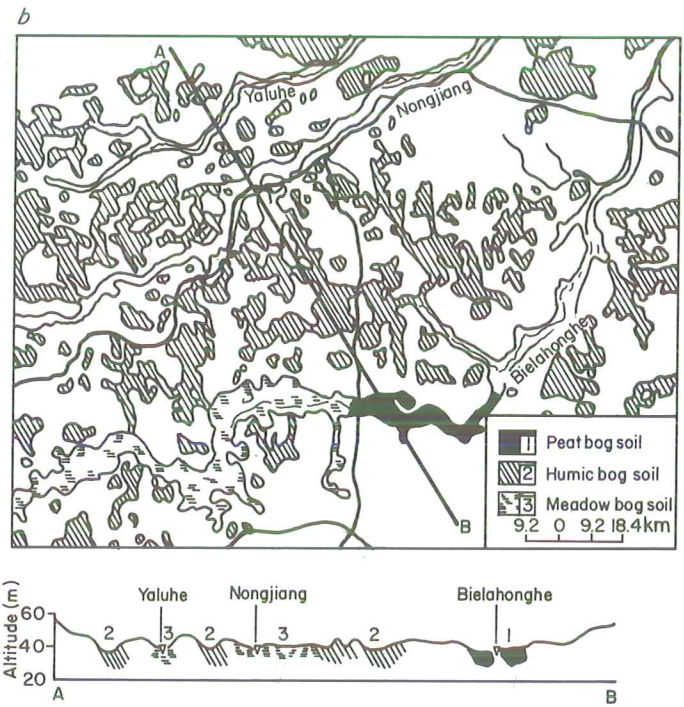
1. Distribution of wetland soils of China. Compiled by Chen Hong-zhao.

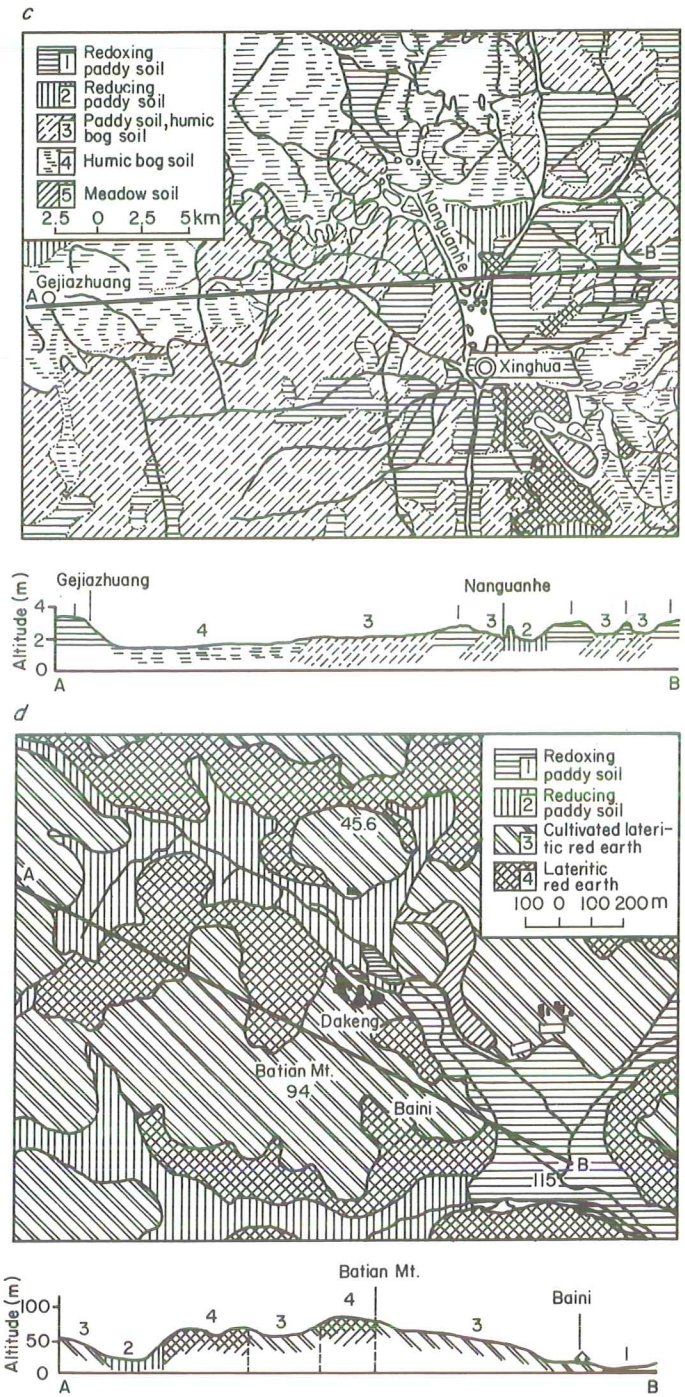
ly warped and settled by silt carried by irrigation water; and the salt content of the soil is generally <0.5%. Bog soils are distributed mainly in depressions on the fringes of alluvial fans or between alluvial fans, in flat valleys of large rivers, and in lowlands along the lakes, but there are some differences between the east part and the west part of the region. With a higher annual rainfall and longer time of submergence, the steppe area in the east of the region is dominated by humic bog soils and peat bog soils with lower salt contents, whereas the desert area in the west, with low annual rainfall and short-term submergence, is dominated by meadow bog soils and humic bog soils, generally with a salt content in the surface strata of >0.8%, being dominated by sulfates and chlorides.

Siallitic wetland soil region

The siallitic wetland region extends from the Northeast Plain to the temperate coniferous and deciduous forests of the mountainous areas of the Southwest Plateau. With a comparatively moist climate and an annual rainfall of 400-1300 mm, this region has more low, flat depressions and a wider distribution of wetland soils than the two previously mentioned soil regions, especially in the Song-nen Plain, the Sanjiang Plain, the Northwestern Plateau of Sichuan Province, and the upper reaches of the Huanghe and Changjiang Rivers, where large areas of bog soils are found (Fig. 2B). The bog rate is 20-30% in the northeast part of the Sanjiang Plain, more than 10% in the Da and Xiao-Xinganling mountains, and generally 3-6% in the Changbai mountains and hilly lands. In this region, there are diverse types of bog soils, most of which are neutral; however, the bog soils on the Northwestern Plateau of Sichuan Province, the peat soils of Yadongduina in Tibet, and the salt-affected bog soils around the Bohai Sea and Huanghai Sea are alkaline, while the meadow bog soils and peat soils in some areas of Heilongjiang are slightly acid to acid. There are large areas of siallitic paddy soils in the plains of the middle and lower reaches of the Changjiang River (Fig. 2C), where paddy soils are derived mainly from yellow-brown earth, meadow soils, and bog soils. The paddy soils in the Northeast Plain are derived from lessive planosol, meadow-black soils, meadow soils, and bog soils, and those in depressions and lowlands at the juncture of the mountains and plains and in the valley lands of the Fen-wei River in North China are derived from fluvoaquic soils. These paddy soils are generally neutral in reaction, only those in the Lixiahe area and the areas along the Changjiang River being slightly alkaline.


a
Moyu
A
Hetian
B
1 Paddy soil
2 Spot-shaped pattern meadow bog soil
3 Oasis soil
4 Gravel alluvial fan
5 Sand dune
4 0 4 8km
Altitude (m)
3000
1500
0
Hetian
4
3
1
3
2
5
Groundwater table
A
B


b
A
Yaluhe
Nongjiang
Bielahonghe
B
1 Peat bog soil
2 Humic bog soil
3 Meadow bog soil
9.2 0 9.2 18.4km
Altitude (m)
60
40
20
Yaluhe
Nongjiang
Bielahonghe
2
3
2
3
2
1
A
B



2. Distribution of wetland soils of different areas of China. a) the southwestern plain in Talimu Basin, Xinjiang, b) the northeastern part of Sanjiang plain, Heilongjiang Province, c) the Lixiahe Region, Jiangsu Province, and d) the coastal hill area, Guangdong Province.

Allitic wetland soil region

The allitic wetland region lies in the eastern Himalaya Mountains, the Minshan Mountains, the Daba Mountains, and the red earth region south of the Changjiang River. With a humid climate having an annual rainfall of 800-1000 mm, the region is characterized by the widest distribution and the most diversity of wetland soils in the country. The allitic paddy soils are predominant. The elevation where these soils are distributed increases gradually from east to west. The highest limit of rice planting in this region is about 2,600 m above sea level. Siallitic paddy soils are distributed in river and lake plains and deltas, carbonated paddy soils on karst corrosion depressions and on alluvial deposits of calcic purple shales in valley bottoms, salt-affected paddy soils in coastal plains, and acid sulfate paddy soils in the river outlet areas. In this region there are few bog soils -- only sparse areas on lake beaches, depressions in river valleys, or mountain tops -- with a bog rate of only 0.2%.

NATURAL WETLAND SOILS -- BOG SOILS

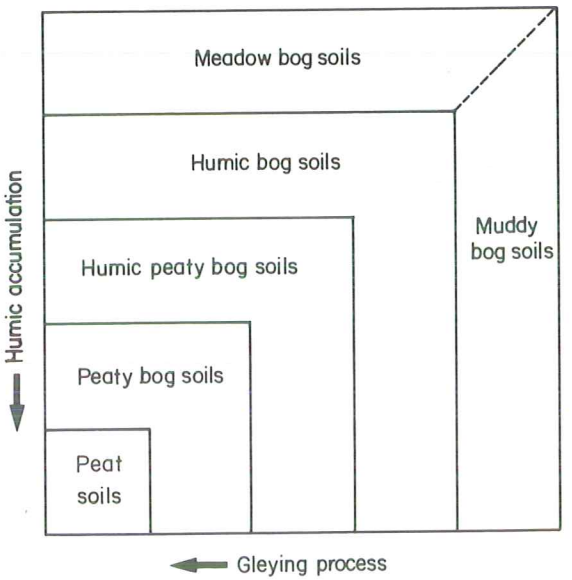
Formation of bog soils

Bog soils are developed under the long-term influence of surface water and groundwater. A thicker humic horizon, even a peat horizon, is gradually formed in the upper soil profile as a result of the insufficient decomposition of organic matter in the soil; and because of the influence of submergence and reductive substances produced by the decomposition of organic matter, the lower part of the soil profile is always in a reduced state and dominated by gleyzation.

According to the intensity of humus accumulation and gleyzation, bog soils may be divided into meadow bog soils, muddy bog soils, humic bog soils, humic-peaty bog soils, peaty bog soils, and peat soils. As shown in Figure 3, with increased humus accumulation and gleyzation, the soils develop in the direction of peat soils.

Types of bog soils

Bog soils may be divided into four great groups, viz., salt-affected, carbonated, siallitic, and allitic bog soils. The salt content of salt-affected bog soils is more than 0.5%. The SiO_2/Al_2O_3 of allitic bog soils is below 2.2, and the clay minerals are dominated by kaolinite. Under each great group, these soils may be subdivided into five subgroups by the intensity of humus accumulation and gleyzation.



3. Evolution of bog soils.

Meadow bog. Meadow bog soils are found in flat valleys, lowland plains, and the margins of disk-shaped depressions. Although there is no standing water on the soil surface, the soils are usually wet and sometimes waterlogged for short periods. In the surface soil, there is more humus, most of which is derived from grass roots or raw humus (A), having granular or fish-egg like structures; the subsoil has mostly transitional horizons (BG) with a lighter color and some rust spots; and the bottom soil is composed of gley blue or light gray gley horizons (G).

Muddy bog. Muddy bog soils are distributed in low-lying areas of lake, beach, and river floodlands. On the soil surface, the standing water is commonly connected with a river or lake. When the river or lake water rises, a large amount of suspended matter is deposited on the soil, and when the river or lake water recedes, the soil is still saturated with water. Such soils have no grass root horizon nor peat accumulation. The surface layer (A) has a lower content of humus, and under this horizon is the G horizon.

Humic bog. Humic bog soils are distributed in terraces, wide valleys, and beaches of lakes and old river courses. During the rainy season or during flooding, the soil surface is usually submerged for a short while, but after autumn the water level falls below the soil surface. The duration of submergence is longer than that of meadow bog soils, and there is no significant accumulation of peat. The surface layer is the

dark humic horizon (AG) with fewer grass roots. The structure of these soils is not as clear as that of meadow bog soils, and the lower part of the soils is the G horizon of blue-gray color. Sometimes the soils have an A-AG-G profile.

Peat humic bog. Peat humic bog soils are distributed in relatively cold and humid regions, generally on the outer fringes of peaty bog soils. The soil surfaces are submerged all year round. The development of soil horizons is very clear: the surface layer is the peat horizon (AT) with a thickness of about 20 cm and many grass roots; under the peat horizon is a well-decomposed AG horizon; further down is the blue-gray G horizon.

Peaty bog. Peaty bog soils occur in the northeast region and on the Qingshai-Xizang Plateaus. There is standing water on the soil surface and much peat accumulated in the surface soil layer. The peat horizon (T) has a thickness of 20-50 cm. Below is a G horizon. The content of organic matter may be up to 78% in the peat bog soils of the subalpine steppe soil belt of the Xizang Plateau.

Peat soils. Peat soils generally have a T horizon with a thickness of 0.5-2.0 m or more. Underneath is the G horizon, but sometimes a humic transitional horizon may be found between the T horizon and the G horizon. The peat horizon is usually more than 30% ash and slightly acid. In some classification systems the peat soils are considered Histosols, while in the soil classification system of China they are still regarded as hydromorphic soils.

ANTHROPOGENIC WETLAND SOILS -- PADDY SOILS

Features of paddy soil formation

Paddy soils are anthropogenic wetland soils. For the purpose of amelioration and utilization of soils for rice cultivation, measures are adopted in accordance with local conditions, including digging trenches, building dikes, terracing, and adopting seasonal irrigation -- resulting in alternating reducing and oxidizing conditions and bringing about the characteristic movement of materials of paddy soil that is induced by reducing eluviation and oxidizing illuviation. Under such influences, there occurs in the profile of paddy soils the diagnostic horizon that characterizes them as an independent type.

The formation of paddy soils has two aspects: wet cultivation-manuring and reducing eluviation-oxidizing illuviation. Wet cultivation includes land leveling, tillage, weeding, puddling of the fields and fertilizing, especially the application of organic manures. The most important processes taking place simultaneous-

ly with the reducing eluviation-oxidizing illuviation include dissolution, reduction, complexing (13), and ferrolysis (1), but not mechanical leaching. Mechanical eluviation is the mechanical translocation of clay particles brought about by the water along pores of the soils. The dissoluted elements are mainly K, Ca, Mg, especially K; reduction refers primarily to the translocation of polyvalent elements including F, Mn, Co, and N (12) under reducing soil conditions because of increased solubility of the elements induced by the decrease of valence. Complexing may improve the eluviation of Fe and Mn under reducing conditions. Ferrolysis implies the substitution of Fe ions and the appearance of H on the exchange sites after drainage, then the H is substituted by Al and ultimately the soils are induced to become acid, bringing about the collapse of the clay minerals. The various processes mentioned are interrelated and constitute the general features of the formation of paddy soils. Judged from the coefficient of aqueous migration, the sequence of the elements in percolating water in red earths is $Ca>Na>Mg>K>SiO_2>P$, Mn, Fe, and Al, whereas that in paddy soils derived from red earths is $Ca>K>Mg>Na>P>Fe>SiO_2>Al$ (Table 1). This is shown by the fact that in the formation process of paddy soils, besides the eluviation of Fe and Mn, the activation and eluviation of Ca, Mg, P, and sometimes Co and Ni are also enhanced. Under some conditions, translocation of Al might even occur.

Paddy soils have unique genetic horizons. The plow horizon is greatly affected by cultivation and manuring; it is generally divided into three subhorizons: the muddy horizon (Ag1) on the surface layer below which is the cloddy horizon (Ag2), and the massive horizon (Ag3), which sometimes has gley spots in winter. The plowpan (P), below the plow horizon, is formed gradually by compression due to plowing. With a more or less laminate structure and a thickness of 8-10 cm, it is compact and able to prevent percolation of the water in the field. The redoxic mottling horizon (B), below the plowpan, has rust spots and streaks and

Table 1. Chemical composition of percolation water.

Water	Composition (mmol/litre)						
	Ca	Mg	K	Na	Al[a]	SiO_2	P
Irrigation water	0.28	0.053	0.038	0.026	–	0.025	0.001
Percolation water of red earth	0.11	0.049	0.015	0.22	tr	0.27	0.008
Percolation water of paddy soil	1.48	0.79	0.079	0.17	0.01	0.21	0.015

[a] – not identified, tr = trace.

has been designated as the illuvial horizon (3, 4). It has also been called the percogenic or perco-eluvial (W) horizon (2, 11); the former stresses oxidizing illuviation; the latter emphasizes percolating eluviation. Here the mottling horizon is used to stress the characteristics of alternating oxidation and reduction and of eluviation and illuviation of materials. There is an angular, blocky structure because of alternation of dryness and wetness and the accumulation of clay particles, bases, Fe, Mn, and even Co and Ni in the horizon. In the formation of paddy soils, eluviation and illuviation of bases and Fe occur, but without remarkable influence on Al (6), whereas in the formation of podzolic soils, there is translocation not only of bases, Fe, and Mn, but also of Al. Therefore, the mottling horizon differs from the B horizon in podzolic soils. There are sometimes lime concretions in the B horizon of paddy soils; however, the concretions are usually rich in Fe and Mn, which indicates that the B horizon of paddy soils differs significantly from the illuvial horizon of calcareous soils. Therefore, the mottling horizon may be used as a diagnostic horizon for paddy soils. In accordance with the intensity of oxidation and reduction, the mottling horizon may be subdivided into the oxidic mottling horizon (Bm), redoxic mottling horizon (Bg), and mottling horizon with gley spots (Br). The mottling horizon where the substances eluviated from the upper soil horizon are oxidized by free O_2 in the lower horizon is regarded as the oxidic mottling horizon. With brown color, it can also be called the brown mottling horizon, being similar to the Bm horizon designated by Matsui (8). The horizon where the substances eluviated down from the upper horizon are first adsorbed at the exchange sites and then oxidized after drainage is regarded as the redoxic mottling horizon, generally with coating illuviated; therefore, it is also called the gray Bg horizon, equivalent to the Bmg horizon without gley spots designated by Matsui. The Br horizon is formed under weak alternation of oxidation and reduction. Because of its blue color, it is also called the blue mottling horizon, corresponding to the BgG horizon designated by Kanno (7) and the Bg horizon designated by Grant (5). Besides, under strong eluviation, an albic horizon (L) can also be found.

The G horizon is not a product of the formation of paddy soils. Having been formed as a genetic horizon of the paddy soil profile, it is of great significance in classification.

Distinction between paddy soils and bog soils

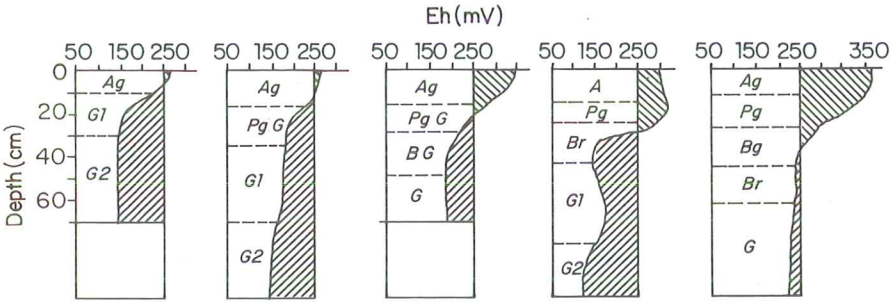
Paddy soils have originated mainly from automorphous soils, meadow soils, and bog soils. After rice was planted, the automorphous soils and meadow soils were

converted from nonhydromorphic soils into hydromorphic soils, and the hydrothermal condition of the original soils was changed fundamentally. So there are evident differences between paddy soils and their original soils. But how to distinguish paddy soils from bog soils is a question concerning the place of paddy soils in the classification of hydromorphic soils.

For reclaiming and utilizing bog soils for planting rice in China, the commonly adopted measures have been drainage, mud manure application, raising the field level by adding earth, and other measures, all of which result in the separation of surface water from groundwater. Since the original reduced state of the bog soils is changed and the processes of oxidation and reduction now alternate, paddy soils derived from bog soils start to differentiate from an Ag-G profile that ultimately develops into an Ag-Pg-Bg-Br-G profile (Fig. 4). Meanwhile, the activities of organisms are enhanced, the original peat process is stopped, the organic matter starts to break down, and the C-N ratio decreases. The alternation of dryness and wetness promotes the immobilization of P. Generally, bog soils are formed by deposition under immobile water conditions. The soil texture gets finer from the lower to the upper part of the solum after planting rice, because of the application of mud and manure and because of mechanical eluviation; and the clay particles gradually migrate downwards. What is most important is that the original bog soil profile is differentiated from a mottling horizon, which is the characteristic horizon of paddy soils. In the beginning it is the Br horizon and then it may be further developed into a redoxic Bg. Paddy soils, though they can be developed from bog soils, are significantly distinct from bog soils.

Types of paddy soils

Paddy soil is a term used in genesis and classification of soils, while in land utilization the terms rice soil or rice field are used. It is not true that all



4. Evolution of paddy soils originating from bog soils.

rice soils can be regarded as paddy soils. Only when the soil, through rice planting, possesses certain essential characteristics may it be regarded as a paddy soil.

In classification, the soil-forming conditions, processes, and soil properties should be taken into consideration. Paddy soils under the conditions of seasonal submergence, cultivation, fertilization, and manuring are characterized by reducing eluviation-oxidizing illuviation, while the mottling horizon as the product of the forming processes may be used as a diagnostic horizon. Only soils with those features mentioned above may be called paddy soils; soils without them, although planted to rice, cannot be called paddy soils.

According to the developmental stages, paddy soils as well as bog soils are classified into four great groups: the salt-affected, carbonated, siallitic, and allitic paddy soils. Each great group may be further subdivided into four subgroups: 1) oxidic paddy soils with surface water and a profile of Ag-P-Bm, 2) redoxic paddy soils that are well-drained with a profile of Ag-P-Bg, 3) reducing paddy soils that are groundwater soils with a profile of Ag-P-Br, and 4) bleached paddy soils with an Ag-P-L profile.

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WETLAND SOILS OF ZAMBIA

R. N. MAGAI

This paper classifies the wetland soils of Zambia as swamps, floodplains, and dambos (seasonally waterlogged grassy areas). These soils cover approximately 20% of Zambia's 750,000 km^2.

One of the major problems relating to the classification of wetland soils according to Soil taxonomy has been the classification using soil moisture and temperature regimes. This problem has been compounded by a lack of precise data to determine the soils accurately at the subgroup level, let alone at the family level. The placement of soils into the tropic taxa has been mainly conjectural.

It is hoped that studies on soil moisture regime now under way will shed more light on the wetness classification, and thereby facilitate the interpretation of Soil taxonomy.

Lying between latitudes 8° and 18°S and between longitudes 23° and 34°E, Zambia consists mainly of a series of gently undulating to flat plateaus, occasionally broken by isolated hills or low ranges of resistant rock. The climate is arbitrarily split into two seasons, wet and dry, with the dry longer than the wet. The average annual rainfall varies from 700 mm in the south to more than 1,500 mm in the north and northwest. The mean monthly temperature ranges from a minimum of 16°C in June and July to a maximum of 24° in October.

The country is subdivided into 2 broad climatic zones, one north of the 1,000-mm isohyet and the other south of it. With few exceptions, all soils north of this isohyet are deeply weathered, strongly leached, acidic, and low in exchangeable cations (10 me/100 g clay). Soils south of the line are generally less weathered, moderately acid to neutral, and retain nutrients fairly well.

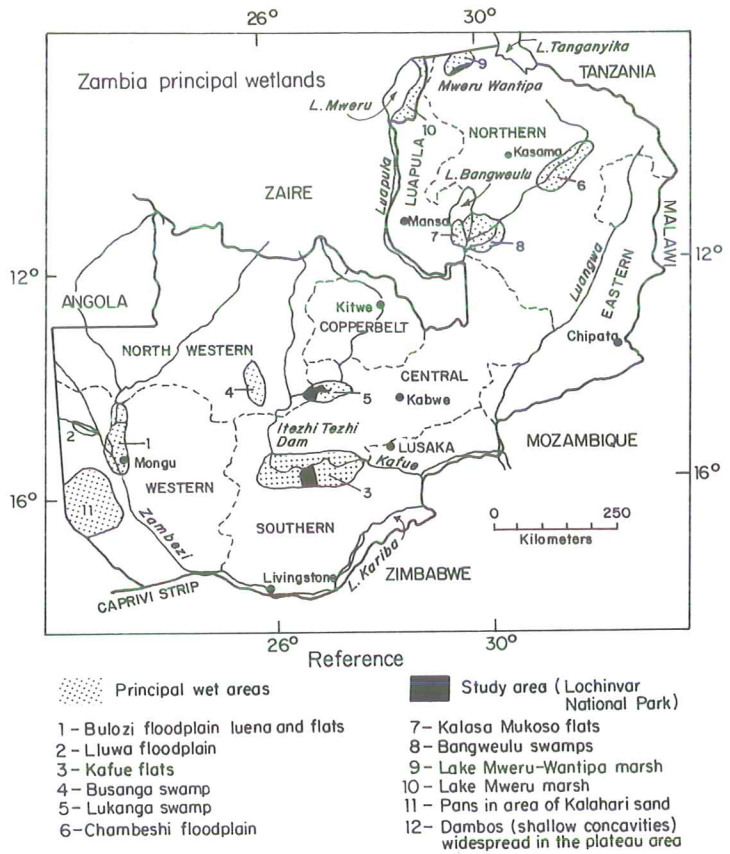
Wetlands are areas that are either periodically wet and periodically dry or permanently flooded with a water layer not exceeding several meters (3). This

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definition clearly excludes open waters that are several meters deep but does include permanent swamps, floodplains, and dambos[1]. Based on this definition, wetlands occupy slightly more than 20% of Zambia's area of 750,000 km^2 (Fig. 1). This paper classifies Zambian wetlands and their soils, identifies problems encountered in the classification of these soils using Soil taxonomy (5), and proposes some amendments.

OCCURRENCE AND DISTRIBUTION OF WETLANDS

The wetlands of Zambia can be identified by a combination of three factors: 1) mode of formation, 2) physiographic position, and 3) moisture regime. The following are the broad divisions of wetlands whose modes of formation are apparent in the definitions.



1. Principal wetlands of Zambia.

[1] Dambo is a vernacular term defining a shallow, grassy depression that is seasonally or perennially wet.

Swamps

A swamp is a vast, usually inundated, depression that consists essentially of floating vegetation and wet peaty land. It is more or less permanently waterlogged. Ferreira (2) identified two basic morphological units of a swamp area: 1) an outer belt, which is flooded annually, and 2) the main swamp, which is permanently flooded and covered with floating vegetation. Small swamps in the high-rainfall zone support a lush vegetation.

Floodplains

Floodplains are zones along major river systems that are low-lying and seasonally flooded. Major floodplains several kilometers wide occur along stretches of the Kafue, Zambezi, and Chambeshi rivers. Being made up of a complex pattern of lagoons, cut-off river channels, ox-bow lakes, levees, and terraces, these plains have a highly variable relief. They are flooded toward the end of the rainy season.

Dambos

Dambos are seasonally or permanently wet grassy valleys, depressions, or seepage zones on slopes. The first two often show a catenary sequence of soils, being well drained on the upper slopes and poorly to very poorly drained in low-lying areas. Dambos have a polygenetic origin, but they are often essentially alluvial deposits and nearly always underlain by laterite at some depth (in some cases at considerable depth).

Ferreira (2) tried to rationalize the definition of a dambo to emphasize its land-use potential and redefined it as "an area of land where the water table, either seasonally or permanently, is located in the upper 20 cm of the soil, often reaching the ground surface itself and occasionally rising to 0.5 m above the surface during the rainy season."

Verboom (6) proposed the following classification of dambos based upon their acidity.

- Sour dambos are usually developed on sandy and peaty soils derived from more acidic parent material and old alluvium.
- Sweet dambos are formed mainly on basic parent material and recent alluvium and have a pH slightly higher than 7. These are confined mostly to the wetter parts of the country in Northern, Northwestern, and Copperbelt Provinces and coincide with basic parent materials. They are, however, also widespread in the southern half of the country.
- Intermediate dambos are generally found on soils developed from mixed sediments and have a pH of 5.5-7.0.

A classification of dambos based on their moisture regime, using wetness criteria proposed in Zambia's Land Use Planning Guide (4), would be more useful. An attempt is being made to improve upon the wetness classification through use of groundwater tubes to determine depths and fluctuations of groundwater movements and then to relate these to existing soil morphological features. Conclusions can be drawn that are valid over wider areas and that will be particularly useful in establishing wetness classes during routine soil surveys.

CHARACTERISTICS OF WETLAND SOILS

There is a fair amount of literature on the wetlands of Zambia, especially the dambos, but in most instances soils data are lacking. The omission of soils information stems from the traditional desire to retain dambos for water conservation and microclimate control alone, except those for rough grazing in tsetse fly-free areas. Essentially, the studies have been confined to ecological features (species composition). It was formerly felt that cultivation of dambos would grossly damage the headwaters. Lately, though, the policy has been slightly changed to allow utilization of the dambos for agriculture under strictly controlled conditions.

Brammer (1) conducted the most comprehensive study on dambo soils and a large portion of the information presented in this paper is drawn from his report.

Swamp soils are the least investigated among the wetland soils. The Brammer study was confined mainly to the Bangweulu swamps in Northern and Luapula provinces, and the soils studied were located on relatively higher parts (fringes) surrounding the swamps. No information is available for soils of the lower lying areas that are permanently wet.

All the soils examined have black, mucky, or highly humic topsoil consisting largely of decomposing animal droppings and trampled grass. The 15- to 30-cm-thick surface horizon overlies mineral soil layers that range from loamy sand to clay texture (Chimburi series), but which get heavier with increasing depth. The subsoil color is usually dark-grayish brown to gray and is strongly mottled with yellow or brown. The organic topsoil is medium acid, and the acidity increases with depth. Correspondingly, their base saturation is lower in Ca, Mg, and K than that of most adjoining plateau soils. The wide C-N ratios in the topsoils suggest that N might be relatively deficient.

Brammer (1) classified these soils according to Soil taxonomy into a new subgroup provisionally termed the Humic Fluvaquents (now the Humaqueptic Fluvaquents). Their placement in the Fluvic great group of the Aquents was based on the assumption that the

organic C content would remain above 0.2% at 125 cm. They were established in the humic subgroup because base saturation was below the 50% limit set for the mollic subgroup.

Although a tropic subgroup indicates the isotemperature regime in which a dark-colored topsoil is allowed, no distinction is made according to base saturation. Hence the creation of humitropic and mollitropic subgroups should be considered.

Dambo soils can be divided into broad categories as follows:

- Gray dambo soils that are gray mottled loams to sands with dark gray to black topsoils and occupy the center of the dambos. The dambo upslopes have pale-brown to almost white sands with dark-colored topsoils, variably mottled in the lower layers. Such dambos are acid in the northern half of the country; in the southern half, they may be weakly acid at the surface but become alkaline below and have a much higher base saturation. Because of insufficient available information, the USDA system has not been attempted, though the less acid soils might be assumed to be in the Tropaquent taxa.
- Black dambo clays would qualify in the order of Vertisols, and the organic soils ("Dambo peats") would be classified under the Troposaprist or Tropohemist great groups.

Among the floodplains, the Kafue flats soils and the Zambezi floodplain soils were studied in relatively greater detail.

The Kafue flats soils (studied in Lochinvar Park) have very dark topsoils with varying muckiness (decomposing animal droppings). The topsoil texture ranges from silty or sandy clay loam to clay. The subsoils of most profiles are dark gray, cracking clay with hard lime nodules present at variable depth and with varying degrees of mottling. Ferrolysis has been observed, leading to the development of light colored and very acid topsoils.

In Soil taxonomy, soils that developed on recent alluvium are classified as Mollic Fluvaquents. The more developed associated soils include Vertic Tropaquept, Histic Pellustert, Entic Chromustert, and Entic Pellustert. The latter soils are usually more conspicuous in gilgai depressions than on ridges.

Other soils occurring in the floodplains are Udorthentic Pellustert, Udorthentic Chromustert, Abruptic Tropaqualf, and Aquic Haplustalf.

The Zambezi floodplain is further represented by soils belonging to Aeric Tropaquept, Aeric Fluvaquent, Hemic Troposaprist, Typic Natraqualf, and Natraqualfic Quartzipsamment[2].

[2] Not described in *Soil taxonomy.*

PROBLEMS IN THE APPLICATION OF SOIL TAXONOMY

Some problems in the application of Soil taxonomy have been mentioned in the preceding pages. Another recurring problem is the lack of adequate laboratory data to classify the soils further at the family level. The lack of precise data on the soil temperature and moisture regimes that determine the placement of many soils at the great group and subgroup levels of the USDA system has restrained the use of some of the taxa units. For example, the tropic subgroup has been used with caution. Similarly, actual moisture regime has not been measured. In particular, the relation of profile morphology to aquic moisture regime and the distinction between present-day aquic and possible "paleaquic" characteristics raise difficulties in classification and mapping. Clearly, more and longer term data are required before these parameters can be used satisfactorily for Zambian soils.

The other point requiring clarification relates to the mollic epipedons. It has been felt that mollic epipedons that are loamy or clayey are usually hard or very hard when dry, and quite massive. As a matter of fact, no hydromorphic Mollisols have been noted in Zambia so far. Either the base saturation of the epipedon or of the subsoil is too low, or the A-horizon is too thin. Two soil series come closest to the Aquoll:

- Kawimbe -- Typic Haplaquoll: coarse to fine silty, mixed, but in this series the base saturation of the topsoil or of the subsoil, or of both, is below 50%; and
- Jivundu -- Fluventic Haplaquoll: clayey, mixed, calcareous, but in the one profile of this series found so far, the epipedon is too thin (15 cm).

Besides, one aquic subgroup of the Mollisols may occur on the levee (dry litongo) -- a sandy, siliceous Aquic Haplustoll -- but a high base saturation in these soils is abnormal. Usually these soils are classified as Dystropept, however, without having a cambic horizon. Maybe an entic subgroup should be introduced to indicate the presence of an umbric horizon and the absence of a cambic horizon in this particular kind of Dystropept. Hydromorphic Spodosols (Aquod) have not yet been found. Probably the groundwater flow in the Spodosol area is high enough to cause removal of the leachates. Some enrichment of the subsoil with organic matter is found only in the better drained Spodosols in the uplands. However, the accumulation of organic matter in the topsoil, very common in the more hydromorphic soils of the Spodosol area, results in Humaquepts or even Histosols.

The Appendix gives a detailed example of the kind of classification problem encountered when applying

Soil taxonomy to Zambian soils. To summarize, the following modifications in Soil taxonomy are suggested:

- Add an entic subgroup in the Dystropepts
- Add a petroferric subgroup in the Ustorthents
- Add a natraqualfic subgroup in the Quartzipsamments
- Add an ustic subgroup in the Quartzipsamments
- The orthoxic or ustoxic subgroup in the Quartzipsamments is not relevant because of difficulties in determining the oxic characteristics.
- A mollic subgroup in the Natraqualfs is unsure because of the massive structure and (very) hard consistency when dry in the "mollic" epipedon
- Add mollic and humaqueptic subgroups in the Tropaquepts
- Add fluventic subgroups in the Haplaquepts and Tropaquepts
- Add an abruptic subgroup in the (Aquic) Kandiustults
- Add humaqueptic, mollic, aeric, psammentic, plinthic, and perhaps oxic subgroups in the Tropaquents
- Add an aquic subgroup in the Haplumbrepts

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Appendix. An example of a classification problem in using Soil taxonomy in Zambia

The Kungu series are imperfectly drained, moderately shallow to very deep, brownish-yellow to pale-yellow (10YR - 2.5Y) soils with a sand to sandy loam to topsoil over a clayey subsoil, and with low-activity clay, low to medium base saturation, usually with plinthite at depths below 50 cm.
Profile CH - 11 is an example of a Kungu sandy loam. The soil occurs on dambo fringes and lower plateau slopes. The diagnostic horizons are either argillic, oxic, or cambic, and are overlain by an ochric epipedon. An albic horizon may be present.

If an argillic horizon is present, the soils usually key out as Oxic Plinthaquult, sandy to coarse loamy over clayey, siliceous, isohyperthermic.

If an oxic horizon is present, the soils key out as (Aeric) Plinthaquox, sandy to coarse loamy over clayey, siliceous, isohyperthermic. "Aeric" is used because the soils do not meet the requirements set for the proposed distinction between Typic Plinthaquox and other subgroups (Soil taxonomy, p. 325). Chromas of the horizons overlying the horizon that contain plinthite range from 2 to 4. "Aeric" is put in parentheses because an aeric subgroup is not yet defined.

If a cambic horizon is present, the soils do not key out as Aquepts because of the color requirements set for the cambic horizon (Soil taxonomy, p. 230). Following the key, some soils are then classified as Aquic Dystropept, sandy to coarse loamy over clayey, siliceous, isohyperthermic, because of the presence of mottles with a chroma of 2. Others are classified as Ustoxic Dystropept, sandy to coarse loamy over clayey, siliceous, isohyperthermic, because of the high chroma of the mottles. Because the presence of plinthite is not indicated, it is proposed that a plinthic subgroup in the Dystropepts be included.

In both Ultisol and Oxisol the aquic character is included at the suborder level, implying that the whole pedon is saturated with water for part of the year. However, in the Inceptisols, the aquic character is introduced at the subgroup level (or not at all), indicating that only the lower part of the pedon is saturated with water for some period of the year. Still, the hydrological regime of the Kundu series is uniform. Obviously, the color requirements set to indicate the aquic moisture regime at the suborder level do not match among the orders. This may ultimately lead to misinterpretation of the soil data, and consequently, to possible wrong recommendations and mismanagement.

Profile No. Ch - 11

Depth (cm)	Analytical data								
	International				Mechanical analysis			U. S. D. A.	
	Coarse sand 2.0-0.2 (%)	Fine sand 0.2-0.02 (%)	Silt 0.2-0.002 (%)	Clay 0.002 (%)	Silt 0.002 -0.05 (%)	Fine sand 0.05-0.2 (%)	Medium sand 0.2-0.5 (%)	Coarse sand 0.5-2.0 (%)	Texture
0-14	24	53	5	18	14	44	19	5	SL
20-54	13	40	6	41	13	33	11	2	SC
54-120	8	34	3	55	10	27	7	1	C

Depth (cm)	Chemical data										
	Organic C (%)	Total N (%)	Ex. Ca (meq)	Ex. Mg (meq)	Ex. K. (meq)	Ex. Na (meq)	CEC (meq)	BSP	pH ($CaCl_2$)	Av. P Ecx10^6 (ppm)	CEC (meq/100 g clay)
0-14	0.78	0.070	0.9	0.3	0.21	0.01	2.3	61.7	4.6	8	12.7
20-54	0.27	0.062	0.3	0.1	0.13	0.01	2.8	19.3	4.1	2	7.0
54-120	—[a]	—[a]	0.4	0.1	0.19	0.01	3.0	23.7	4.0	—[a]	5.4

[a] not determined.

Profile No:	Ch - 11	*Mapping unit:*	F	Date sampled
Soil name:	Kunu sandy loam	*Slope:*	3-5%	21-2-1975
Location:	N. Province, Chinsali district	*Vegetation and use:*	Grassland with some scattered *brachystegia utilis*	
Physiography:	Dambo side			
Parent material:	granite:	*Permeability:*		
Drainage:	Imperfect	*Land capability class:*	$S_3w \frac{I\ (15)\ B\ E\ E\ F}{B\ \ w_2\ (2.5Y\ 6/2)}$	

Profile description:

Horizon depth (cm)		*Description*
A_1	0-14	Very dark grayish brown (10YR 3/2), moist and grayish brown (10YR 5/2) dry *sandy loam;* weak to moderate fine and medium subangular blocky; slightly hard dry, very friable moist; many very fine and fine pores; many fine roots; gradual smooth boundary.
A_3 (g)	14-20	Light brownish gray (2.5Y 6/2) moist *sandy clay, loam* with common, fine, and medium faint light yellowish brown (2.5Y 6/4), moist and grayish brown (2.5Y 5/2), and light gray (2.5Y 7/2) mottles; weak to moderate, medium subangular blocky; sticky, nonplastic wet, friable moist, slightly hard dry; many very fine and fine pores; few fine roots; diffuse boundary.
B_1 g	20-54	Pale yellow (2.5Y 7/4) moist *sandy clay* with common medium distinct reddish yellow (7.5YR 6/6), moist, light brownish gray (2.5YB 6/2), moist and light yellowish brown (2.5Y 6/4) mottles; weak to moderate, fine, and medium subangular blocky; very plastic wet, firm moist, very hard dry; many very fine and fine pores; diffuse boundary.
B_2 g	54-150+	Pale yellow (2.5Y 7/4) moist *clay* with many medium distinct reddish yellow (7.5 YR 6/6), moist, light brownish gray (2.5Y 6/2), moist and light yellowish brown (2.5Y 6/4) mottles; weak to moderate medium subangular blocky; very hard dry; many very fine and fine pores.

WETLAND SOILS IN VIETNAM

VO-TONG XUAN and NGUYEN VY

Vietnamese wetland soils either occur naturally because of diversified hydrologic and physiographic conditions or have been formed artificially as a result of efforts to bring more land under rice production. French and Vietnamese soil scientists have done soil studies since the 1930s, but it was not until 1961 that Russian, Dutch, and Vietnamese pedologists completed a general soil map of Vietnam. The classification of acid sulfate soils in the Mekong Delta by the U.S. Soil taxonomy system was completed in 1982. Based on the national system of soil classification, the following wetland soils in Vietnam were identified: 1) alluvial of fluviatile and marine origin, including acid sulfate, 2) sandy ridge and regosol, 3) red-yellow podzol, 4) red-brown latosol, 5) low humic gley, 6) gray degraded, and 7) peat. There is an urgent need for an effective system of soil classification in Vietnam to promote better land use.

Rice is the oldest domesticated crop of the Vietnamese people. It is grown in almost any soil, from the sandy regosols along the coastal areas to the alluvial soils in the river floodplains to the loamy latosols in the Central Highlands. Rice-growing environments are highly diversified and result in various methods of planting. Therefore, the formation of rice soils may differ from that in other countries, i.e., a plowpan is absent in many profiles. On many soil types, land is prepared under totally dry conditions (for floating rice); on others, zero tillage is the normal practice (for double transplanted rice and zero tillage direct-seeded rice). Literally speaking, wetland soils in Vietnam are not necessarily wet throughout the entire season.

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SOIL CLASSIFICATION

Earlier works by French (Castagnol, Auriol, Roule, etc.) and Vietnamese (T. T. Khoi, T. T. Ky, L. P. Loi, etc.) soil surveyors in the 1930s and 1940s provided a general division of soil types in Vietnam. The first systematic soil survey in southern Vietnam was done by F. R. Moorman (1) under the auspices of FAO in cooperation with Thai Cong Tung, Nguyen Hoai Van, and others. Simultaneously, in northern Vietnam, soil scientists carried out a reconnaissance soil survey. Afterwards more detailed soil surveys were made by the Soil Survey Division of the Agricultural Research Institute in Saigon and by the Institute of Soils and Fertilizers and the Institute of Agricultural Planning in Hanoi (3).

After 1975, the Institute of Agricultural Planning, in cooperation with other soil research groups, completed a schematic soil map of the country, semi-detailed soil maps (scales 1/50,000 to 1/250,000) of all the provinces, and, recently, detailed soil maps (scales 1/5,000 to 1/10,000) of important production areas.

The classification systems used by various authors were based on the Soviet system modified by the FAO-UNESCO system (in northern Vietnam) and on the 1983 American classification system modified by the FAO-UNESCO system (in southern Vietnam). At present, a descriptive system is being used to classify soil groups. It uses vulgar terms and some adapted terms from the FAO-UNESCO system. Some temporary soil properties such as pH of fresh soil, sulfate and chloride contents, and others were dropped as criteria in classification. The system is constantly under revision.

In 1982, L. J. Pons (pers. comm.) was the first to attempt to apply the U.S. Soil taxonomy (2) system, with several modifications, to classify some acid sulfate soils in the Mekong Delta. Another revision was made in early 1984 by L. J. Pons, R. Brinkman, and M. E. F. van Mensvoort to classify alluvial soils in the Mekong Delta. These efforts are also being constantly revised because of the complicated nature of acid sulfate soils in this region.

During 1984-85, a land resources inventory program for the Mekong Delta based on the Soil taxonomy system will be carried out. A revised general soil map is expected. Until there is a clear understanding of the new classification system leading toward official adoption, the descriptive system is still valid, and the following descriptions of wetland soils in Vietnam are based on the present system.

WETLAND SOILS IN VIETNAM

Alluvial soils

Alluvial soils comprise most of the rice soils in Vietnam. The two largest river systems in the country, the Red River and the Mekong River, as well as a network of smaller rivers, have deposited fluviatile sediments on top of marine clays, which are sometimes overlain by brackish water sediments.

Fluviatile alluvials. Fluviatile alluvials are found with depths varying from 0.5 to a few metres. In the Red River and Mekong Deltas, they are neutral to slightly acidic; in the small deltas of mountainous central Vietnam, they are moderately acidic. These river floodplain soils are subjected to annual flooding from August to October in the Mekong Delta, while in the Red River Delta, floods are controlled by a system of high dikes. With balanced fertilization emphasizing N, grain yields of short-duration, high yielding modern varieties (MV) of rice can reach 8 t/ha per crop. Double or even triple cropping is possible with additional irrigation. Tables 1 and 2 show some properties of these soils and their responses to fertilization.

Marine alluvials. These are found along coastal plains, often underlain by brackish water sediments at various depths. They are temporarily intruded by saline water during the dry season. Rice cultivation is possible only during the rainy season. In regular weather, it is possible to obtain 8 t/ha with MVs such as IR42, with about 150 kg N/ha. There is little response to P or K.

Acid sulfate soils. Acid sulfate soils are important alluvial soils that occupy about half of the total

Table 1. Some properties of the main rice soils of Vietnam.

Soil group	pHKCl	CEC (meq/ 100 g soil)	Ca+Mg (meq/ 100 g soil)	Clay fraction (%)	Organic matter (%)	N (%)	P (%)	K (%)
Neutral fluviatile alluvial soils	5.5-6.5	15-28	10-17	15-22	1.6-2.5	0.15 0.21	0.04 0.07	1.3 1.8
Acid sulfate soils	2.8-4.2	12-17	4-7	12-26	1.4-4.2	0.08 0.17	0.01 0.04	1.3 1.6
Marine alluvial soils	6.5-7.8	13-26	10-20	14-21	1.5-3.0	0.14 0.18	0.03 0.06	1.5 1.8
Degraded gray soils	4.0-5.0	6-10	2-6	<10	0.5-1.2	0.06 0.10	0.01 0.03	0.2 0.4
Sandy ridge regosols	4.2-5.4	5-8	2-4	<8	0.5-1.0	0.05 0.10	0.01 0.03	0.2 0.2

Table 2. Response to NPK fertilization of some rice soils in Vietnam.

Soil group	Yield response (kg rice grain/kg fertilizer)			
	N	P	K	Farmyard manure
Neutral fluviatile alluvial soils	8.0-13.5	0.0-2.3	1.0-2.7	40-50
Acid sulfate soil Low humid gleysoil peat soil	without P: −2.0 −1.5 with P: 4.0-9.0	5.5-22.4	2.5-5.0	35-50
Marine alluvial soil	7.2-13.2	1.2-5.1	0.8-2.4	40-55
Light soils (sandy ridge regosols)	10.0-25.5	6.5-13.6	5.7-9.5	35-40

area of the Mekong Delta and parts of the coastal areas of central and northern Vietnam. Preliminary surveys jointly carried out by the Agricultural University of Wageningen (the Netherlands) and the University of Cantho have shown that several types of acid sulfate soils exist in the Mekong Delta, most of which are not classified in Soil taxonomy (2). They belong largely to the orders Entisol, Inceptisol, and Histosol and may be classified into the great groups Aquents, Fluvaquents, Sulfaquents, Aquepts, Sulfaquepts, Tropaquepts, Humaquepts, and Tropofibrists (L. J. Pons, pers. comm.). They can be further divided into the subgroups typic, sulfic, humic, pale, entic, dystic, etc. The main characteristics of these soils with regards to rice cultivation are Al^{3+} and Fe^{2+} toxicities and severe P deficiency. With appropriate water management, i.e., a shallow drainage system providing drainage only during the first 2 mo of the rainy season, and also with small-dose split application of superphosphate fertilizers, it is possible to obtain reasonable yields with MVs (Table 2, 3).

Sandy ridge regosols

Sandy ridge regosols are mainly loamy sand to sandy loam found parallel to the present coastlines, especially near areas with white or yellow sand dunes, in central Vietnam. They were old beaches that had been desalinized, with medium to very poor nutrient contents. Rice is grown during the rainy season. If sufficient NPK fertilizer and organic manure are provided, MV rice can give high yields. During the dry season, farmers dig shallow wells in the middle of the sandy fields to irrigate their rice.

Red-yellow podzols

Red-yellow podzols constitute the most widespread soil group occurring on weathering products of more or less

Table 3. Effects of different kinds and dosages of P fertilizers on the growth and grain yields of IR9129-169-2-3-5 grown on a humic Sulfaquept at Hoa-an, Phung-hiep, Hau-giang, averages of two crops, 1981-82.

Treatment no.	Kind of fertilizer	Dosage (kg P/ha)	Panicles[a] (no./m^2)	Filled grains (no./m^2)	1,000-grain wt (g)	Av yield[a] (t/ha)
1	Control	0	258.33 d	7,366	22.6	1.46 c
2	Superphosphate	8.74	370.37 bc	8,578	23.3	2.07 bc
3	Superphosphate	17.48	367.31 bc	12,706	22.7	2.72 ab
4	Superphosphate	26.22	464.50 a	15,412	23.4	2.96 ab
5	Phosmak	8.74	361.32 bc	10,634	22.9	2.08 bc
6	Phosmak	17.48	394.78 abc	13,725	23.3	2.99 ab
7	Phosmak	26.22	378.13 cd	15,639	23.5	3.09 ab
8	Apatite	17.48	476.03 a	13,606	22.2	2.89 ab
9	Apatite	34.96	416.66 ab	15,217	24.8	2.74 ab
10	Apatite	52.44	373.95 bc	14,730	23.8	2.32 b
11	Thermophosphate	8.74	424.99 ab	14,029	23.3	2.20 b
12	Thermophosphate	17.48	404.76 ab	15,511	23.3	2.98 ab
13	Thermophosphate	26.22	420.83 ab	16,914	23.6	3.55 a

[a]Separation of means by Duncan's multiple range test at the 5! level.

acid rocks and old terraces of alluvial sediments. Wherever there is a good source of irrigation water, rice can be planted with reasonable yield. These soils are usually puddled very thoroughly before planting to minimize percolation. A sufficient dose of P fertilizer should be provided together with N fertilizers. MV rice yields of up to 7 t/ha are possible, and sure water control enables farmers to plant 3 crops/yr.

Red-brown latosols

Red-brown latosols are found widely on the weathering products of basalt. The reddish-brown clays develop to depths of up to several tens of metres. Good irrigation schemes in central Vietnam have turned several zones with this type of soil into good rice land. Heavy organic manuring plus NPK fertilization are essential in boosting MV rice yields to 7-8 t/ha, and 3 crops of rice per year are possible under complete-water-control conditions.

Low humic gley soils

Low humic gley soils are closely associated with the podzols but situated in low-lying areas that have a periodic high water table. The low humic gley soils are very poor soils, giving low rice yields. Phosphorus fertilizers are particularly needed (Table 2).

Gray degraded soils

The weathering processes on old terraces of large rivers have formed the gray degraded soils, which are extremely poor in nutrient content, needing large doses

of NPK fertilizer (Table 1, 2) and extra organic manure in order to sustain reasonable rice yields. Only areas with sufficient irrigation are being planted with rice.

Peat soils

Peat soils occur sporadically throughout Vietnam. In the Mekong Delta, peat was found in the backswamps between the river floodplain and the coastal plains. Young marine or brackish sediments, often peaty clays, are found underneath peat layers. When the peaty topsoil is not more than 50 cm, farmers burn the fibrous materials and grow rice directly on it; or they make ridges to plant a short-duration upland crop on the ridge and transplant MV rice in the furrows. Rice yields are low because of a high percentage of empty grains, possibly caused by Cu deficiency.

CONCLUSION

Classification and characterization of wetland soils in Vietnam are still in an early stage. Because of the lack of an effective system of soil classification in the country, standard procedures in site characterization have not become popular among agricultural extension workers as well as administrators at various levels. Technology transfer therefore is still based on empirical observations; this situation has caused serious problems in the application of the technology from one soil to another soil. There is a great need for training Vietnamese soil researchers in modern soil classification and soil surveys to promote better land-use evaluation in the country.

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WETLAND SOILS OF CHILE

W. LUZIO

In the central part of Chile, most soils with excess wetness are Ochraqualfs and Haplaquolls. Only the moisture regime makes these soils different from the adjacent drier soils, but the yields on wet soils are lower than those of the same crop grown on soils with a xeric moisture regime. Organic soils are more productive than mineral ones.

In the Andean Mountains, wet soils are found in depressed basins with impeded drainage. Organic (Borofibrist) and mineral (Cryaquent) soils can be identified even though there are no differences in how farmers use them.

Most of the wet soils on volcanic ash are Placaquepts. They are rather shallow soils with impeded drainage and are used mostly for dairy or beef cattle after the natural forest has been cleared. The Placaquepts occupy the flattish part of the landscape associated with the outwash plains of the periglacial zone. The presence of the placic horizon between the ash and the unrelated glacifluvial substratum is considered the main cause for the impeded drainage of these soils.

This paper considers three important wet soils in Chile: those in the central part of the country, those in the Andean Mountains, and those derived from volcanic materials.

WET SOILS IN CENTRAL CHILE

The wet soils that are found in the central part of Chile are associated with a lowland landscape. Sometimes they are in closed basins without natural drainage, at other times in depressed sedimentary formations. Except the wet soils, which have an aquic

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moisture regime, the soils in the central part of the country, between latitudes 32° and 38°S have a xeric moisture regime. Two types of soils, mineral and organic, can be identified. Very well defined seasons characterize the area: cold, rainy winters and dry, hot summers. The mean annual rainfall varies from 300 mm in the northern part to 1,500 mm in the southern part. The soil temperature regime is thermic (8).

In various soil surveys of the region (1, 2), Ochraqualfs and Haplaquolls appear as the most important soils with excess wetness. The condition of very humid soils, besides the flat and depressed position in the landscape, is related to the presence of impervious layers in the profile, or to high clay content that decreases the water permeability, or to both.

The very low permeability of many Chromoxererts of the area, which stems from their high clay content (>50%), makes them suitable for rice. With yields of 6.4 t/ha common, they are considered very good rice soils. But these Vertisols are beyond the scope of this paper because they are not recognized as wet soils.

Three examples of soils with an aquic moisture regime are described in Table 1. The clay content is not very high, even in the B_{22t} horizon of the Typic Ochraqualf. Thus, the condition of poorly drained soils is a consequence of the lower position they occupy in the landscape. The organic C content is rather low;

Table 1. Clay, organic carbon, pH, cation exchange capacity, and base saturation of some mineral soils of central Chile.[a]

Mineral soil	Clay (%)	Organic carbon (%)	pH (water) (1:1	CEC (meq/ 100 g)	Base saturation (%)
		Cumulic Haplaquoll (Gatera S. series)			
Ap	31	5.8	5.5	35	75
C_1	31	1.0	6.9	29	86
C_{2g}	36	0.3	7.0	28	86
		Typic Ochraqualf (Los Lingues S. series)			
Ap	24	2.2	4.9	24	57
B_1	22	0.5	5.9	19	69
B_{21t}	29	0.4	6.0	24	74
B_{22t}	48	0.2	6.0	28	78
II B_{23}	28	0.4	6.6	36	84
III C	25	0.3	6.4	31	85
		Aeric Ochraqualf (Yaquil S. series)			
Ap	18	1.9	5.1	14.8	61
A_3	15	0.3	6.0	9.7	73
B_{2tg}	19	0.3	6.1	12.4	79
B_{3g}	21	0.2	6.2	14.6	81
C_g	20	0.1	6.2	13.9	81

[a]Source: Chile, Minagri-Sag (2).

only in the Ap horizon is there some accumulation, although not significant (2). Cation exchange capacity, pH, and base saturation values show no difference from those of dry soils in the same region; hence, the differences are mostly morphological because of the presence of gley and prominent mottled horizons, which indicate that the water table stands near the surface, at least during winter.

These soils are used for crops, but in general the results are rather poor. A rice yield of 3.2 t/ha is common in these soils compared with 6.4 t/ha in some Chromoxererts. Wheat yields are only 2.1 t/ha as a dry crop and 3.1 t/ha under irrigation using $NaNO_3$ and superphosphate as fertilizers. Maize yields of 6.4 t/ha are considered only reasonable (2). Sunflower is also grown on these soils, but no yield figures are available.

In the organic soils, the organic horizons normally rest on gleyed mineral materials 40-80 cm in depth that appear as lithological discontinuities in the profiles. The figures from two different profiles (Table 2) show that the soils have a $CaCO_3$ accumulation in the organic matter, mostly in the upper horizons. Micromorphological studies have proved that the $CaCO_3$ is found in the form of calcareous nodules whose origin has been interpreted as genetic accretion from soft calcareous structures. They become indurated by desiccation produced by artificial drainage (3). While these soils keep their wet condition with the water table near the surface, they are used mostly for pasture, maize, and some vegetables. With artificial drainage they can be subjected to more intensive agriculture; some farmers have planted grapes, one of the highest income crops in Chile.

Table 2. pH, organic matter, $CaCO_3$, and electrical conductivity of some organic soils of central Chile.[a]

Organic soil	pH (water)	Organic matter (%)	$CaCO_3$ (%)	Electrical conductivity (mmho/cm)
		Medisaprist pedon 2		
Oap	7.6	34	12.8	2
Oa_2	7.5	35	12.7	1.4
Oa_3	7.3	50	7.2	1.3
II C	4.2	2.5	0.7	2.3
		Medisaprist pedon 2		
Oap	7.8	30	10.2	1.7
Oa_2	7.8	31	9	1.7
IIC_1	6.2	2.9	1.9	0.6
IIC_2	5.7	2.2	1.3	1.1

[a]Source: Honorato and Garrido (3).

WET SOILS IN THE ANDEAN MOUNTAINS

Wet soils are found everywhere in the Andes, from north to south, but in this paper only the soils that occur in the northern part, from latitude 18° to 30°S, will be considered.

From a geological point of view one of the most important Andean formations is composed of ryolitic lavas that originated during the Tertiary Period. This formation occupies an extensive territory in Chile, from latitude 18° to 28°S extending through the Andean Mountains at an altitude of >2,800 m. The mean slope is about 7%. Besides the ryolite, andesite and quaternary basalts also appear. Due to previous water flows, this formation has been extensively eroded, resulting in numerous deep creeks. At the present time the region is arid and there are only very small, seasonal streams. There are a few narrow valleys with very limited amounts of water in which agriculture is restricted to carrot, onion, maize, and alfalfa, the last used to support small herds of sheep and camelids (llamas and alpacas).

Eastward into the Andes, where the slopes are very steep, frequent depressed areas are found among the hills. These are sedimentary basins with restricted drainage where organic soils or mineral soils with high organic matter content have developed. The water table is at or very near the surface and the amount of salts throughout the profile is very high. These depressed sites do not occupy extensive areas, but are very important for the local farmers because they are used for pasture for the nearly 200,000 camelids and sheep that are maintained in these very isolated regions with restricted natural resources for agriculture. The soil moisture regime is aquic and the soil temperature regime is assumed to be cryic, although there are no data to prove it. Where the reducing conditions are permanent or almost permanent, gley horizons are developed (5).

In the organic (Borofibrist) soils, the water table is near the surface more than 6 months a year and sometimes all year round. In the first case (Table 3, Parinacota), although the water table is near the surface, almost all year there are no gley horizons. It is suggested that this is due to the movement of the groundwater and consequently there is no reducing environment. Furthermore, the soil shows increasing acidity with depth up to extreme acidity beyond 82 cm. In the second case (Table 3, Tiloposo), the reaction is moderately alkaline, and gley horizons start at 34 cm (5); the water table is not as mobile as in the former case.

With regard to the mineral (Cryaquent) soils, the first example (Table 4) is a soil whose surface has a very strongly alkaline reaction that decreases with

Table 3. Pyrophosphate and pH of some organic soils in the Andean Mountains.

Depth (cm)	Pyrophosphate	pH (water) 1:1
	Borofibrist (Parinacota)	
0-9	5Y 8/2	7.3
9-60	5Y 8/2	5.8
60-82	5Y 8/2	5.6
82-95	5Y 8/2	4.1
	Borofibrist (Tiloposo)	
0-9	5Y 8/3	8.1
9-34	5Y 8/3	7.8
34-67	5Y 8/1	8.0

Table 4. pH, organic matter, $CaCO_3$, extractable cations, cation exchange capacity, and electrical conductivity of some mineral soils in the Andean Mountains.

Mineral soil	pH (water) 1:1	Organic matter (%)	$CaCO_3$ (%)	Extractable cation (meq/100 g)				CEC (meq/ 100 g)	Electrical conductivity (mmho/cm)
				Ca	Mg	Na	K		
			Cryaquent (Isluga)						
A_1	9.2	5.8	9.3	4	35	50	11	18	10
A_2	8.4	3.0	—	61	7	9	4.7	11	22
B	8.8	1.3	—	11	2	2	2	12	2
C_1	7.6	0.9	—	3	1.6	0.9	0.9	8	1
C_{2g}	7.4	0.5	—	2	0.9	1.4	0.9	5	1.4
			Cryaquent (Turi)						
A	9	10.3	21	85	30	144	11	30	150
C_1	9.2	13.8	55	34	14	15	4	32	14
C_2	9.1	6.9	70	28	8	9	1.5	22	6
C_{3g}	9.1	11.1	—	27	4	6	1.5	14	4

depth and becomes mildly alkaline to neutral at 66 cm. The gley horizons start at 66 cm and the mottled zone at 22 cm. Still having an aquic moisture regime, this soil is considered drier than the organic soils (5). The second example, another Cryaquent from Turi (Table 4), shows a very strongly alkaline reaction throughout the profile. The more serious problem of this soil is in the surface horizon (15 cm), where the values of extractable Na and electrical conductivity are very high. The gley horizons start at 29 cm, but the mottles start at the surface (5).

The most important species associated with both types of soil -- organic and mineral -- are Oxichloa andica, Distichia muscoides, and Distichlis humilis. The camelids and sheep use this vegetation during the 9-10 months a year when the area is not frozen.

There are no clear tendencies with regard to the properties of the soils that occupy these depressed basins. However, the land use is similar, whether the

soils are organic or mineral and whether their reactions are acid or alkaline. The essential point is that there is enough water in an arid region to support a grassland that maintains the livestock of the area.

WET SOILS ON VOLCANIC MATERIALS

The word ñadi is used to identify a specific drainage condition in the landscape, namely a swamp with a firm subsurface and hence one that is transitable with care. In fact this word refers more to a broad ecological concept than to a soil. It implies poor drainage conditions, subdued relief, dense forest cover, and firm ground at no great depth below the surface (9). Nevertheless, Chilean soil scientists normally refer to "ñadi soils" to indicate the soils developed under these special conditions. Ñadi soils are derived from volcanic ash and are classified as Placaquepts.

The ñadi soils are found in Chile between latitudes 38° and 41°S between the Andes and the Coastal Range. They occupy >50% of the lowland landscape. The mean annual rainfall fluctuates from 1,000 mm in the northern part to 3,000 mm in the southern. The soil moisture regime of the area is udic except for the ñadis, which are considered aquic. In areas where the mean annual rainfall is between 1,500 and 3,000 mm, with no month in the year with less than 100 mm, the ñadis attain their maximum development (9). The soil temperature regime is mesic and isomesic (8).

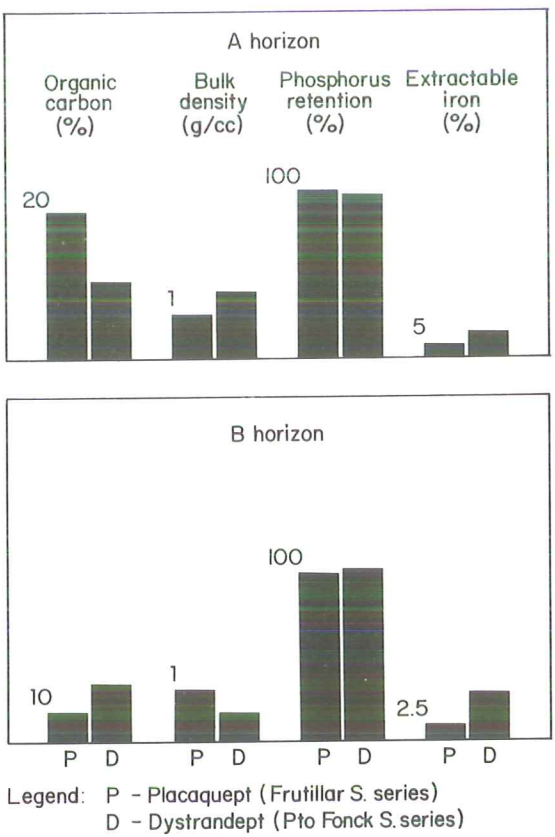
Most ñadi soils occupy the flattish part of the landscape. They occur in association with better drained soils also derived from volcanic ash that occupy the more strongly undulating rolling and hilly parts of the landscape. Most of these soils, locally known as trumaos, are Dystrandepts.

Normally, ñadi soils are thin (25-50 cm) to moderately deep (50-100 cm), with clear horizon differentiation. In the common profile of a ñadi, the black epipedon contains >10% organic C. In areas where the rainfall exceeds 2,000 mm/year, the ñadi soil develops a histic epipedon and the natural forest vegetation becomes replaced by sedge communities. There is a dark-brown Bs with subangular structure over a distinct yellowish B, which in turn rests abruptly on a placic horizon. The substratum is a glacifluvial deposit that corresponds to the outwash plain of the piedmont glaciers from the Andes and is composed of more or less rounded cobbles and pebbles. During the dry season, the upper part of this deposit is firm and indurated, but this condition disappears during the rainy season, when it is moistened.

The placic horizon, black to reddish-black in color, is roughly horizontal and more or less continuous. Even though the origin of the placic horizon is

not clearly understood, it has been suggested that the main cause is due to the downward movement of Fe mobilized during the season when the ñadi soils are saturated. When the Fe reaches the contact zone between the ash-size particles and the gravel-size particles from the outwash, it is oxidized and immobilized. There is also a physical process involved in the precipitation of Fe due to the contrasting pore size of the ash and the gravel. Some data have shown that the placic horizons are also rich in Mn, and consequently it is supposed that the migration of the Fe has taken place jointly with the Mn.

Much more Fe has been mobilized downward in the ñadi soils than in the adjacent well-drained Dystrandepts (Fig. 1). Considering that there are no significant mineralogical differences among the ashes that are the parent materials for both types of soil, this is the reason why the values for extractable Fe are higher in the Dystrandepts than in the Placaquepts (6).



1. Organic carbon, bulk density, phosphorus retention, and extractable iron in the A and B horizons from a Placaquept (P) and a Dystrandept (D).

In the clay fraction, allophane is the most important mineral. Chlorite and gibbsite are also present in most of the soils (4) (Table 5). Imogolite is the only important mineral in the Frutillar ñadi soil, indicating that desilication has been an important process. Imogolite has been found mainly in environments with a low Si-Al ratio (E. Besoain, pers. comm.).

With regard to the origin of the typical landforms associated with these soils, there is geological and morphological evidence to suggest that the ñadis are related mostly to the outwash plains of the periglacial zone. Toward the northern part, some ñadis are found in old terrace positions, and toward the south some of them are associated with local lacutrine deposits. At present there are two main hypotheses to explain the deposition of the volcanic ash over the unrelated substratum, the eolian and the baywater mechanisms.

One explanation is that the ashes were deposited mainly in the form of loess rich in volcanic glass. This idea does not satisfactorily explain the overall distribution of the ñadi soils, first because they occupy only depressed positions of the landscape, and second because the dominant wind system in that part of the continent is from west to east, meaning that the source of volcanic materials is located on the wrong side with regard to wind direction.

A more feasible explanation is the alluvial origin. The presence of rounded gravels at different depths in several profiles is one argument; another is the position in the landscape; and finally there were some volcanic eruptions during the 1960s during which this process was confirmed. Significant amounts of ash fell into the rivers, the river beds were considerably widened, and the ash was transported into streams and spread over long distances.

One of the most interesting features of these soils is the lack of morphological evidence of poorly drained materials. Under natural conditions only very weak incipient indications of mottling in the subsoil are found. The degree of mottling contrasts with the extreme seasonal wetness of these soils. After the

Table 5. Mineralogy of the clay fraction from some volcanic ash soils.[a]

Volcanic ash soil	Dystrandepts		Placaquepts	
	Pto. Fonck	Pto. Octay	Frutillar	Alerce
Allophane	5-5-5-5-5-5	5-5-5-5-5-	5-5-5-5-5-5	5-5-5-5-5-5
Imogolite	?	1-1-1-1	4-3-3-4-1-1	?
Chlorite	3-2-3-2-2-2	3-3-3-3-3	1-2-3-2-2-2	1-2-2-2-2-2
Gibbsite	1 1	1-1-1-2-2	1-1-1-1-1-1	1-1-2-1-1

[a]Source: (E. Besoain, pers. comm.) .5 = dominant, 4 = abundant, 3 = common, 2 = present, 1 = scarce.

natural forest is cleared and cropped for many years, with artificial drainage, more prominent mottles in the subsoil are found, although not frequently.

More significant changes in the vegetation are produced when farmers clear the forest. The natural forest looks dense and vigorous and seems to be without visible nutrient deficiencies. After clearing, farmers normally plant grasses for dairy or beef cattle, and sometimes wheat or barley. At that time marked nutrient deficiencies appear in crops and pastures, the most important being P and N deficiencies.

In Figure 1, a Dystrandept and a Placaquept are compared for organic C, bulk density, P retention, and extractable Fe (6). Organic C is normally higher in the A horizon of the Placaquept. On the contrary, the B horizon of the Dystrandept shows higher organic C. The histic epipedon of the Placaquept determines the lower bulk density in the upper horizon. On the contrary, in the B horizon the bulk density is higher in the Placaquepts, probably because of subsidence and subsequent compaction after artificial drainage. No differences were detected with regard to P retention. Extractable Fe is higher in the Dystrandept throughout the profile, suggesting that the migration of Fe to form the placic horizon has been more significant in the Placaquept.

Using Soil taxonomy (7), the Nadis that have a histic epipedon meet the requirements for the Placaquepts, even though no appropriate subgroup has been provided. With regard to the new order of Andisols, they meet the requirements for the Aquand suborder only if they have a histic epipedon. Furthermore, no Placaquand great group has been recognized up to now although some changes are expected after the Chile-Ecuador Workshop of January 1984.

There are still extensive areas to be cleared and used for agricultural production, but we must expand our knowledge about this environment to minimize the negative ecological alteration and at the same time to make good use of our natural resources.

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RECOMMENDATIONS

Noting that the wetland soils of Africa, Latin America, and South and Southeast Asia comprise some 550 million ha, of which fewer than 150 million ha are now used to grow rice and other crops, the Workshop recommends that:

- research be undertaken to characterize wetland soils (whether currently used for agriculture or not) in terms of hydrological, chemical, physical, morphological, mineralogical, and biological properties and processes in order to facilitate the extrapolation of results of soil and crop research to as large an area as may be economically utilized (The specific recommendations of the four Working Groups, which follow, give detailed guidance on the research needed to make this possible. The use of satellite imagery in support of the hydrological aspects of land characterization and classification was not discussed at the meeting but is recognized as an important adjunct to existing methods of wetlands assessment);
- donor agencies and implementing organizations such as SMSS, IBSRAM, INSFFER, IBSNAT, FAO, UNEP, and the national agricultural research organizations be encouraged to support research, meetings, and workshops that provide opportunities for interaction among and combined efforts of soil and land classification groups, survey and land evaluation groups, and soil fertility and crop production scientists; and
- the sponsoring organizations -- INSFFER, SMSS, and the Bureau of Soils -- and the host institution -- IRRI -- be commended for the excellent organization, facilities, and support services provided for the Workshop on Characterization, Classification, and Utilization of Wetland Soils.

WORKING GROUP REPORTS

GROUP A. CHARACTERIZATION OF WETLAND SOILS AND NEEDED RESEARCH IN RELATION TO THEIR BETTER UTILIZATION

The following characteristics should be accurately recorded if wetland soils are to be properly classified and utilized.

1. Morphology

Changes in degree of wetness affect the morphology of wetland soils. Descriptions of morphology must therefore either include a statement of conditions at the time of description, with predicted states at seasonal extremes, or be made with the soil under extreme conditions.

The description of morphology should include:

- a color distribution pattern -- differences between interior and exterior of peds, or of the bulk soil if peds are not clearly expressed;
- a quantification of oxidized and reduced regions, made by use of a grid, and point counting;
- chemical characteristics of components -- determined by hydrochloric acid and lead acetate paper (carbonates and sulfides will effervesce differently), color of residue after ignition (black = Fe-Mg silicates, white = organic matter, red = other Fe minerals), a-a' - dipyridil (or other reagents) to determine if Fe^{2+} is present, and hydrogen peroxide test (manganese dioxide effervescence).
- micromorphometric (optical and submicroscopic) characterization of microstructures and porosity (puddling effects, ease of regeneration).

2. Physical characteristics

- soil water content and potential;
- compressive strength, penetrability, shear strength, and aggregate stability determined at different soil moisture contents;

- porosity, bulk density, and swelling pressures at different moisture contents;
- pore size distribution determined from water retention (at least at 0.1 and 5.0 bar saturation before and after puddling), and using nonpolar liquids and mercury intrusion methods;
- water conductivity, saturated and unsaturated, and infiltration rate at field capacity;
- air conductivity and oxygen diffusion rate (ODR) determined at field capacity; and
- specific heat, heat capacity, and heat conductivity.

3. Electrochemical properties
   - redox potential (Eh or pE) of the soil in defined conditions;
   - redox buffer capacity;
   - pH -- wet (without and with hydrogen peroxide treatment) and dry (systematic studies will be necessary to interpret differences in wet and dry pH);
   - pH buffer capacity (wet, without and with peroxide treatment);
   - cation exchange capacity -- wet and dry; again systematic studies are needed; and
   - electric conductivity and composition of soil solution, including organic anions, which affect the chemical oxygen demand.

4. Organic matter
   - quantity present, determined from CO_2 evolution, rather than from consumption of O_2, on oxidation or combustion;
   - carbon-nitrogen ratio;
   - redox buffer capacity, and chemical oxygen demand;
   - micromorphology research is needed to characterize coarse organic matter under permanently wet and alternately wet and dry conditions;
   - soil microbial biomass;
   - ash content of extracted organic matter; and
   - interactions with heavy metals.

5. Mineral matter
   - iron and manganese minerals should be characterized using preferential extraction methods (oxalate, dithionite), micromorphology, before and after preferential extraction, and differential x-ray diffraction analysis;
   - sulfide mineral characterization methods are needed; and

- clay minerals and allophanes should be characterized by x-ray, infrared, and thermal methods.

The technique of sampling reduced soils needs special attention, since oxidation after sampling changes many of the features mentioned. (Methods dealing with the content of nutrient and toxic elements are addressed by Working Group D.)

GROUP B. PROCESSES IN WETLAND SOILS AND NEEDED RESEARCH IN RELATION TO BETTER UTILIZATION

In considering processes in wetland soils and needed research in relation to better utilization, technical papers in sessions 1 and 2 noted the following constraints to agricultural production in rice-based cropping systems:

- soil moisture stress;
- excess soil water;
- nutrient availability, deficiencies, toxicities, imbalances, and losses;
- physical problems in puddling and subsequent regeneration of soil structure upon desiccation for dryland crops; and
- development of pans and layers restrictive of root growth and water movement.

Working Group B addressed processes interrelated with soil properties and soil utilization. These processes result in properties that may in turn be characterized and used in soil classification. Furthermore, proper classification of soils is a prerequisite to information transfer on fertility responses and adequate application of cropping systems. Special attention should be given to future research on soils under field conditions.

The goals of this exercise were to determine those processes and resultant properties that are either directly or indirectly related to Soil taxonomy and the utilization of wetland soils for food production.

The wetland soil processes related to soil properties have been structured as shown in Table 1.

The following high-priority research needs have been identified for wetland soil environments:

- verification of processes responsible for current soil moisture regimes and development of hydrological models for predicting the occurrence and duration of soil saturation and redox potentials under selected climatic, soil, and hydrologic conditions;

- determination of the processes resulting from puddling (destabilization of soil structure), including cohesive strength, bonding, hydraulic conductivity, apparent pore volume, and particle arrangement and its persistence as a function of texture, mineralogy, organic matter, and soil chemical properties;
- characterization of the processes responsible for shrink-swell phenomena; formation of cracks, slickenslides, and other structural voids; textural differentiation; moisture retention and desorption; and restrictive pans and surface crusts that are pertinent to water movement and root development (quantification of these processes must be related to specific groundwater and surface water regimes, soil properties, and landform characteristics);
- development of methods of land characterization and classification for biological activities in wetland soils (for example, suitability for azolla utilization or susceptibility to N losses by volatilization); ecological studies of the limnological type and research study on floodwater chemistry;
- further studies to quantify organic matter production, decomposition, humification, and distribution in surface and subsurface horizons under different wetland environments to serve as properties used for Soil taxonomy differentiation and to control nutrient availability to the crops and microbiological activity;
- determination of the intensity/capacity components under wetland field environments that control redox processes: pH changes; dissolution, distribution, adsorption, and desorption of soluble species; and mineral transformations; and
- determination of spatial variability of processes correlated with macromorphological and micromorphological features that can be used as morphological markers of contemporaneous wetlands pertinent to Soil taxonomy and crop growth responses.

Tables 2-4 document the rationale used to formulate the final group report. They include examples of processes, effects on soil, relationship to Soil taxonomy, relationship to utilization, and needed research.

Table 1. Wetland soil processes.

Water-dominated (mostly physical)	Chemical	Related to structural, morphological, and mechanical features	Biological
Periodicity, duration, and direction of saturation	Redox processes (intensity, capacity)	Puddling and regeneration of structure	Noncrop biomass production (aquatic weeds, algae, bacteria, zooplankton, etc.)
Groundwater Permanently near surface Seasonal fluctuation	Migration, transformation, segregation of Fe, Mn, Al, and other micronutrients and macronutrients	Formation of restrictive pans, surface crusts, and clods	Organic matter transformation
Surface water Floodwater Perched water	Salinization, alkalinization, and carbonate accumulation (calcification)	Shrink-swell phenomenon in cracking clay soils, slickenside development, cracking hysteresis, gilgai formation	Decomposition and nutrient recycling
Dynamics of water movement	pH changes, especially in acid sulfate soils	Micromorphological features under different hydromorphic conditions	Humus formation
Dynamics of gas exchange	Ferrolysis	Textural differentiation	Food chains
Processes at water-soil interface zone in submerged soils	Chelation and complexation	Heat flow in nonsubmerged soils	Biological N fixation and immobilization
Heat flow in submerged soils			Rhizosphere effect: exudation, ion exchange, gas exchange, root microbiology
			Nitrogen losses through volatilization and nitrification-denitrification processes

Needed research

Formation, strength, and persistence (micromorphology and submicroscopy) – soil specific
Evaluation of puddling needs in terms of the physical, chemical, mineralogical, and organic composition of the soil – soil specific
Evaluation of the dynamics of nutrient and mobile elements – soil specific
Applicability of laboratory studies to field conditions
Regeneration of soil structure – soil specific characteristics, morphological, differences of aggregates
Toxicities and deficiencies – soil specific
Ripening

Table 2. Puddling.

Effects	Soil	Relation to		
		Soil taxonomy	Utilization	
			Wetland	Dryland
Apparent pore volume	Surface temporal	Mollic or umbric epipedon	Water management	Tilth
Soil strength			Nutrient management	Water availability
Particle arrangement		Translocation of particles to subsoil or accretion of sediments at surface	Toxicities and deficiencies	Drainage
Color			Weeds	Moisture sorption-desorption
N forms and transformation		Differential sediment transport by "erosion"		
Redox and pH				
Other nutrient transformation: P, Fe, Mn				
Biological actions				
Water movement				
Shrink-well				
Interaction of clay and organic matter				
Rooting volume				
Others				

Table 3. Water saturation, periodicity.

Duration	Effect			
	Electrochemical transformation	Chemical transformation	Biological transformation	Physical transformation
Long —depths	Redox	In situ nutrient mobilization	Microflora and microfauna	Color pattern
directions	pH	and availability	(native, biomass)	Colloid accumulation
Short —directions	EC	Mineral transformation	Organic matter transformation (surface, subsoil)	Gaseous exchange
				Water movement
Alternate wetting and drying		Ferrolysis		Cracking pattern — shrink, swell
				Structure, strength
				Ripening
				Translocation: relative, absolute accumulation of elements (Fe, Ca, etc.)
				Clay dispersion, translocation

Soil	Relation to		Needed research
	Soil taxonomy	Utilization (Wetland and dryland)	
Whole	Color patterns for: aquic soils and integrades	Cropping pattern	Differentiation of permanent, long-duration, short-duration, alternate wetting and drying
		Nutrient management	
	Organic matter depth phenomena	Nutrient losses	Classification of water regime
	Diagnostic subsurface horizons	Toxicities and deficiencies	Microspatial pattern of biological redox
		Land preparation	Action relative to water regime, organic matter, biological action, pore distribution
			Electron donors, acceptors
			Ferrolysis — soil specific
			Ripening
			Monitoring and modeling of water regime, etc. (rice and weather program)
			Microphobic features
			Heat flow
			Humic forms and humus characteristics

Table 4. Processes at water-soil interface zone (interaction between floodwater and soil).

Effects			Needed research
Chemical	Physical	Biological	
Redox, redox pattern	Mixing	Activities of micro-fauna and macro-fauna	Water chemistry (concentration and kinetics)
pH, CEC	Convection		
	Heat flow	Algae: diurnal	Colloids in the floodwater
Flux of ions (sources: floodwater, fertilization, and trans-location)	Seed environment	Bacteria	Siltation
		Nutrient transformation	Urease activity: nitrification-denitrification
			Nutrient cycles
			C input, turnover

GROUP C. CLASSIFICATION OF WETLAND SOILS AND NEEDED RESEARCH IN RELATION TO BETTER UTILIZATION

The discussion started on the term "wetland soils." It was stated that wetland soils are not equivalent to "soils with an aquic moisture regime." Most of the latter soils exclude the surface water gleys, although this condition is of major importance for agricultural utilization. The definition of the aquic moisture regime will be rewritten to include the surface water gleys (epiaquic, anthraquic). It was agreed that:

- the soil water status and dynamics should be determined in "benchmark toposequences," with INSFFER sites as the initial locations; research would include the use of auger hole water measures, piezometers, tensiometers, and neutron probes, as well as additional measurements pertaining to rainfall (gauges, self-registering), evapotranspiration (pan-method), irrigation water level, surface drainage, field measurement of relationship of reduction, etc; a detailed soil survey should be made for each site and relevant geomorphological information compiled;
- for the definition of epiaquic and anthraquic moisture regimes, a study of their relation to the environment is needed, with focus on geomorphology, flooding, vegetation, and hydraulic conductivity and climatic data;
- further studies on alternative criteria for use in the definition of the aquic moisture regime consider:

1. including surface water gley in the aquic soils moisture regime and the addition of epiaquic/anthraquic taxa (limits/thickness of soil moisture control sections, etc);
2. methods of defining aquic regimes (boreholes versus piezometers, water transmission, water stagnation, reduction, etc.);
3. methods of defining wet taxa on the basis of morphology:
   a. diagnostic horizons related to wetness (placic, "dasic," "quorizem," calcic, salic histic, suphidic materials, plinthite, albic horizon; bleached ground water horizons; etc.);
   b. horizon boundaries (generally mainly based on color and texture, oxidation-reduction state, or distribution of organic matter, or structure, or difference in root density);
   c. thickness of horizons or layers;
   d. soil color relationships (matrix/intensity/distribution of gray colors and mottles/percentage in terms of quantitative limits, Fe or Mn content or both, root mottling as typical for paddy fields, coatings, etc.);
   e. oxidation/reduction status (tested with a-a'-dipyridil, for example);
   f. texture (clay distribution, etc.);
   g. structure and consistency of relationships (difference in puddled soils, other terms for description);
   h. traffic pans;
   i. cracks;
   j. organic matter relationships (example of lighter colored puddled topsoil higher in organic matter than darker underlying horizon; impact on oxidation-reduction status, etc.); and
   k. concretions, nodules, and other features.

with regard to agricultural utilization, there is a need to differentiate among wet soils in seasonally dry areas; items to be studied are:

1. periods that the soil is moist (or wet) versus dry;

2. cracks, how long open, close when rewetted, etc.; and
3. contrasting soil moisture regimes, which could be expressed as "Ustic Tropaquepts" (for example); and
4. the improved classification of wetland soils enables necessary specifications with regard to utilization, such as

   a. water management, [drainage (pro and con), irrigation (ponded mainly for rice), structural amelioration, including subsoiling, preservation of natural conditions];
   b. trafficability;
   c. structure regeneration (for dryland crops); and
   d. chemical (fertility) relationships.

GROUP D. FERTILITY OF WETLAND SOILS AND LAND CHARACTERIZATION IN RELATION TO SOIL CLASSIFICATION

The group's mandate was to develop recommendations for a better characterization of the rice environment and to relate environment to soil fertility and management practices. The group discussed issues concerning 1) physical and chemical soil properties, 2) hydrological properties, 3) floodwater chemistry, 4) crop management aspects, and 5) soil testing practices now in use for rice cultivation in several Asian countries.

On the basis of the papers presented, the field tour, and the discussions, Group D recommends that the following points be considered.

- The Fertility Capability Classification (FCC) system should be tested and applied to wetland rice soils as a means of grouping together soils with similar constraints.
- The FCC modifier for acid sulfate soils (c) needs further refinement to establish a better limit. An additional modifier for cation imbalance ratios (r) should be developed; additional modifiers for low topsoil organic N (q) and low native available topsoil P (p) should be investigated and incorporated into the system if reliable quantitative limits can be identified.
- Rice fertility and management field trials should classify the soil according to Soil taxonomy at the family level. Emphasis should be given to mineralogical

characterization in relation to fixation and release mechanisms. FCC should not be considered an alternative to Soil taxonomy, but rather a technical system that facilitates the interpretation of Soil taxonomy for agronomic purposes.

- A Hydrological Capability Classification (HCC) system should be developed similarly to the FCC system to characterize in a systematic and quantitative manner extremely important factors such as 1) water table depth during dry and wet seasons; 2) frequency, depth, speed, and duration of natural flooding; 3) quality of irrigation, flood, or groundwater; and 4) other relevant hydrological parameters. A working group should be established to develop the HCC. Hydrological constraints often override soil constraints in rice production. The development of this technical system is, therefore, considered urgent.
- Technical classification systems should be interpreted in terms of specific cropping systems, including rotations of puddled rice with other crops.
- An informal survey of soil testing methods for rice in Asia (see Table 1) indicated that the Olsen-P method receives general acceptance. A critical level of about 10 ppm P is used in several countries. Total Kjeldahl N is widely used but critical levels are not clearly established. Various methods for K are used, but in many cases K is no problem at existing low yield levels. The strengthening of soil fertility evaluation services, including soil tests and correlations with yield responses, should be encouraged in rice-growing countries.
- Varietal differences in tolerance to soil problems should be quantified in terms of external (soil) or internal (tissue) critical levels. More research is needed on the physiological mechanisms involved in the Fe-toxicity syndrome, Al toxicity, and Zn and Cu deficiencies.
- Physical properties pose severe problems in wetland soils. Research is needed on structure regeneration after puddling in cropping systems with upland crops after rice. The use of raised beds after rice should receive more emphasis. Methods for collection and interpretation of data on physical parameters need improvement. It is hoped that the use of soil physical

parameters will be clarified at the forthcoming IRRI conference on soil physical properties of wetland soils in December 1984.

- For upland crops, some nutrient ratios with safe ranges exist. There is an urgent need to establish safe ranges of various ratios and their interactions with other nutrients for rice, and to translate the results into the proposed r modifier in the FCC. A working group to develop the r modifier was formed; it developed the following working hypothesis for the r modifier in the FCC system as an indicator for nutrient imbalances:

Ratios of various nutrients (like Ca:Mg, Mg:K, $\frac{Ca+Mg}{K}$) are sometimes used in upland crops to indicate nutrient imbalances. Safe ranges have been established. In Cameroon, for perennial crops, Ca:Mg was thought safe between 1 and 5, and Mg:K between 2 and 20. This indicates a safe range for $\frac{Ca+Mg}{K}$ of 4 to 120. In Pakistan, Ca:K and Na:K imbalances are experienced on calcareous saline sodic soils, which might be related to the role of certain clay minerals in the release and fixation of nutrient elements.

For rice, imbalances and safe ranges have not been defined. However, data presented in the field guide (Table 2) indicate that excessive $\frac{Ca+Mg}{K}$ ratios are somehow related to Zn and K deficiencies. On site 7, this ratio was 258; 49.8 kg of K resulted in a yield increase of 2.27 t/ha. Information from the IRRI Soil Chemistry Department suggests a relationship between the Ca-Mg ratio and Zn deficiency, with Ca:Mg $\leq$ 2 as a critical limit.

There is an urgent need to establish the safe ranges of various ratios for rice. Ratios for elements other than those mentioned above should be investigated.

Table 1. Some soil test methodologies and critical levels in various countries reported to Group D.

Country	N		P		K		Other remarks
	Method	Critical level	Method	Critical level	Method	Critical level	
Philippines	field trials		Olsen		K		Zn soil tests do not always correlate with yield response
	% OM	< 2 low 2-3 medium > 3 high		> 10 high 5-6 medium < 4 low		75 ppm	
India		> nr	Olsen	some areas gr, other areas nr.	Usually no K problem		Zn soil tests do not always correlate with yield response
	% C	> 1%					
			Incubation + Olsen Bray II	gr nr			
Indonesia Philippines (IRRI)			Olsen For azolla: Olsen P. abs. capacity 1500 mg/ 100 g	7-10 25 gr	K	80	Zn soil tests do not always correlate with yield response
China			Olsen Bray (in soils pH 5)	av K			
Burma	% N		Truog	av K			Storrie index for general fertility status
Pakistan (rice-wheat)	% N	always deficient	Olsen calcareous saline, sodic soils	20	K calcareous saline, sodic soils	150	Sodicity: pH of sat. extract
Malaysia	% N		Olsen		K		
Thailand	% N		Bray II		av K		Recommendations based on yield trials, in combination with soil tests

Table 1 continued.

Country	N		P		K		Other remarks
	Method	Critical level	Method	Critical level	Method	Critical level	
Vietnam	% N		Truog 10		total K	2%	K rarely a problem in deltaic areas
Nigeria	% N		Olsen Truog		N K problem in Niger delta		High pH – Zn deficiency
Cameroon		Only yield trials; no soil tests yet					
Australia							S deficiency by analysis of vegetative tissues and N–S ratios in grains
Nepal	% N		Olsen		av K		

% N = total Kjeldahl N, % OM = Walkley and Black organic matter, av K = available K in NH_4OAc extract meq/100 g., K = K in soil extract ppm, nr = no relationship, gr = good relationship.

Table 2. $\frac{Ca + Mg}{K}$ topsoil ratios of soils visited on field tour in relation to INSFFER trial yields at the site.

Stop no.	$\frac{Ca+Mg}{K}$ in top horizon	Rice yield (t/ha)				Problems
		Dry season		Wet season		
		Control	Highest	Control	Highest	
1	43	3.3	9.7	4.1	5.3	–
2	147	4.2	6.6	3.2	5.2	–
3	34	2.9	7.0	–	–	–
4	200	3.5	4.7	–	–	–
5	74	–	–	3.0	4.4	–
6	118	–	–	4.9	6.3	–
7	258	3.8	[a]	2.3	–	K
8	90			4.4	6.1	–
9	168		–	3.9	5.8	–
10	72		–	4.1	6.2	–
11	–	dryland	–	–	–	–
12	331	na		na		Zn, K
13	295	na	–	na		Zn, K
14	195	–	–	3.2	4.2	Zn, K
15	30	–	–	4.7	6.5	
16	5	na		na		

[a] NP = 5.73, NPK = 8.00.

INTERNATIONAL FERTILITY AND FERTILIZER EVALUATION FOR RICE (INSFFER) SUMMARY REPORT

C. P. MAMARIL

Agronomic results and summaries of the different INSFFER trials, including the economic analyses of the N fertilizer efficiency trials, were discussed and presented. It was suggested that the trials, which showed no significant effect, should not be pooled with the rest in analyzing agronomic and economic response. The lack of significant response in some trials was attributed to high coefficients of variation (CV). However, examination of the results of the 5th International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice revealed that only 4% had CVs greater than 18%. The long-term fertility and P-source trials generally had higher CVs. Collaborators were encouraged to take greater care in the establishment and maintenance of these trials in an attempt to maintain CVs ranging from 5 to 18%, preferably not higher than 12%.

SUMMARY OF RESULTS

Rice yield responses were obtained in 242 of the 271 trials of N efficiency for irrigated rice conducted since 1975. Response to deep placement of urea was significantly greater than that to best split application of urea in 41% of the trials, where a response to N was obtained, and significantly less in 4%. Average responses to sulfur-coated urea (SCU) and to deep-placed urea were similar. On the average, a 1-t/ha yield increase was produced by 50% as much N from SCU or deep-placed urea as from best split application of urea among those trials where split application was inferior to the other practices.

Results from N efficiency trials for rainfed rice showed that deep-placed urea was superior to split application in 47% of the trials in which there was a yield response to applied N. The relative responses to SCU and to deep placed urea were similar. As in the irrigated trials, about 50% as much N was required from SCU or deep-placed urea as from split broadcast urea to produce a 1-t/ha yield increase.

Long-term fertility trials have generally shown that yield responses to N occur for the first crop, to P for the 4th or 5th crop, and to K only after prolonged cropping at the selected sites.

In P source trials, the performance of water-soluble fertilizer P was superior to that of calcined Fe/Al-P on a Vertisol (pH 6.7) and to apatitic phosphate rock on an Ultisol in the Philippines. Responses to residual P during six crops were similar for sources at both locations. In Thailand, yield responses to water-soluble P and apatitic phosphate rock were similar at two locations.

FUTURE PLANS

INSFFER collaborators will try to use the FCC grouping system to classify their respective sites, and to study some of the parameters of FCC to improve the system, if needed. The guidelines prepared by P.A. Sanchez, W. Couto, and S.W. Buol have been distributed to the collaborators present during the workshop; copies will be sent to the rest of the collaborators.

M.I. Bajwa of Pakistan offered to analyze the clay mineralogy of INSFFER sites, especially those that have no access to appropriate facilities. A clay sample of 5-10 kg for each site will be sent to Pakistan. Separation of the clay fraction will be done at IRRI. Therefore, collaborators are requested to send an additional 1-kg soil sample to IRRI for this purpose as well as for routine chemical analyses.

Some collaborators indicated interest in conducting NH_3 volatilization measurements using the methods proposed by J.R. Simpson and J.R. Freney of CSIRO. Those concerned were requested to indicate the required equipment already in their possession so that the needed additional equipment can be determined. It was agreed that, regardless of whether the floodwater samples were sent for analysis to CSIRO or to IRRI, communication and information should be shared with the INSFFER coordinator. The procedure for the NH_3 volatilization measurement will be prepared by Drs. Simpson and Freney and will be distributed by IRRI to the collaborators interested in participating in the project.

The group agreed upon a new N fertilizer-efficiency trial in irrigated rice, to be called the Sixth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice. The trial will consist of 13 treatments, including a water management treatment at all levels of N, and serve as the standard method for applying prilled urea (PU). Two-thirds of the N (as PU) will be applied basally onto mud and broadcast and incorporated without standing water; the remaining third will be applied 7 days before panicle initiation with 5 cm of standing water. Since some of the collaborators expressed concern about the difficulty of controlling water in farmers' fields, to adopt a

standard water management treatment the group agreed that the Fifth International Trial on Nitrogen Fertilizer Efficiency in Irrigated Rice should be continued. Water depth on a plot-wise basis must be measured at the time of fertilizer application.

The Third International Trial on Nitrogen Fertilizer Efficiency in Rainfed Rice will continue unchanged, as will the azolla trial. However, collaborators in the azolla trial have the option of carrying out the same trial without insecticide treatment.

Only two most promising fertilizer applicators will be tested by interested collaborators, one for PU and the other for urea supergranules (USG). All applicators already sent to some countries should be included in the trial, however.

The trial on P sources for irrigated lowland rice will be continued without modification. Cameroon, Indonesia, Pakistan, the Philippines, and Vietnam are continuing the trial. Other countries are encouraged to initiate it, considering that P deficiency in lowland rice soils is relatively widespread.

No changes were made in the long-term fertility trial. Addition of Zn and S could be included as optional treatments, especially where these elements may be limiting and where provisions for additional treatments have been made. More collaborators are encouraged to undertake this trial.

The trial on the integrated use of inorganic and organic fertilizers will likewise continue since it was just started last year and is a long-term project. It should be important in countries where inorganic fertilizer is scarce and expensive.

The group agreed to conduct a collaborative trial on fertilizer efficiency of different N sources in upland rice. The trial will also include the use of a nitrification inhibitor, dicyandiamide (DCD), in combination with the N sources. Likewise, the group proposed the formulation of a trial on the soil fertility management of acid upland soils.

In all the trials, soil and site characterization will be emphasized to improve interpretation of the agronomic results and their translation to other similar areas. If possible, the sites should be classified according to Soil taxonomy and the FCC classification system.

FUTURE ACTIVITIES OF INTERNATIONAL COMMITTEE ON SOILS WITH AQUIC MOISTURE REGIME (ICOMAQ)

F. R. MOORMANN

ICOMAQ is one of the international committees created by the USDA Soil Conservation Service (SCS) under the Soil Management Support Services. Its purpose is to study, review, and revise specific portions of Soil taxonomy in the light of new findings in both field and laboratory. Soils that do not occur in the regions for which the present Soil taxonomy is valid may be incorporated in the proposed revisions.

The committees function as loose associations of scientists, well versed and interested in the subjects dealt with by their specific committees. Most contacts are by correspondence, through circular letters coming from the chairman. Items are also discussed in personal contacts and during workshops, meetings, etc. The outcome of the work is a set of recommendations to SCS for changes and revisions of specific items in Soil taxonomy deemed necessary and desirable to make the system function better on the international scene. The acceptance or rejection of the recommendations is the sole responsibility of SCS. Normally, SCS consolidates proposals, "translates" them into the terminology of Soil taxonomy, and distributes them for testing both in the US and abroad before incorporating them (if at all) in the body of Soil taxonomy.

The specific mandate of ICOMAQ is to review the definition of the aquic moisture regime (also called the aquic regime) and to suggest ways and means to revise, strictly where necessary, the present taxa with an aquic regime at the level of generalization deemed appropriate.

Participants in the Los Baños SMSS-INSFFER workshop discussed several specific items, which may be paraphrased as follows:

- revision of the aquic regime definition of Soil taxonomy;
- introduction of subdivisions of the aquic regime;
- revision, where necessary, of existing taxa with an aquic regime and introduction of new taxa at appropriate levels of generalization; and
- re-examination of related subject matter, such as the definition of the cambic horizon in wet soils, the existing taxonomic problems

with Sulfaquepts and Sulfaquents, and the classification of sloping soils with an aquic moisture regime for which at present only the family level appears available.

REVISION OF THE AQUIC REGIME DEFINITION

The definition of "aquic regime," as it now stands, is ambiguous in several respects. It covers only soils that are wetted from below, having a true groundwater level that rises to the surface, wetting the soils to the surface (free groundwater or the capillary fringe).[1]

A new general definition of the aquic regime should be based on

- depth of the wet state,
- duration of the wet state, and
- degree of reduction.

Obviously the determination of aquic moisture regimes of major soils will require actual measurement of groundwater and surface water by various means, such as water levels through time in open bore holes, piezometer studies, neutron probe, and other measurements under field conditions. Also, attention should be given to methods of determining the degree of reduction in wet horizons, one of which involves the use of a-a'-dipryridyl. For specific soils such as wet Vertisols, other methods of determining wetness and reduction may be required.

The measurements mentioned here and others forthcoming from members and collaborators of ICOMAQ cannot be made by ICOMAQ itself, but will depend on feedback from the field to the Committee. In this respect, it is specifically recommended that measurements of this nature be made at INSFFER trial sites, similarly to those done at certain of IRRI's rice-based multiple cropping research sites.

SUBDIVISION OF THE AQUIC REGIME

The aquic regime as a general term is used to describe soils that are subject to prolonged wetness and reduction within a depth to be defined by ICOMAQ, but which tentatively is placed at less than 100 cm.

The present aquic moisture regime of Soil taxonomy caters to soils that are wet and reducing throughout, i.e. the true groundwater gley soils of the European

[1] The use of soil water states, including definitions of soil wetness, depth classes, and duration classes of the wet state is according to the new *Soil survey manual,* Chapter 4, p. 20-31 (Document 430-V-SSM 1981).

literature. Tentatively, we would use the term orthaquic for this condition with the provision that the wet-reduced state in the surface layers should have a duration of one-twelfth of the time or more (duration class b). The existing term peraquic would be used for conditions in which the groundwater is always at or very close to the surface, as described in Soil taxonomy. For soils with true groundwater wetness and reduction in the lower horizons (aquic subgroup), the term endoaquic is proposed.

Soils with wetness and reduction in the surface horizons to a depth of at least 50 cm, in which the surface wetness is not matched by a corresponding subsoil wetness, are not specifically defined in the present Soil taxonomy. These soils are known as pseudogleys or surface water gleys. For such soils, the term epiaquic may be used on the condition that the present epiaquic subgroups of the Oxisols and Ultisols are renamed.

Finally, the present chairman of ICOMAQ feels that a special subdivision of the aquic regime is needed to cater to well-drained soils that have assumed the characteristics of an aquic surface water regime because of their use for bunded and ponded rice fields. Tentatively, the name anthraquic is advanced for this condition, which might be considered as a special kind of epiaquic regime.

A future task of ICOMAQ is to define and quantify these variants of the aquic moisture regime.

REVISION OF EXISTING TAXA AND INTRODUCTION OF NEW TAXA

Once a redefinition of the aquic regime and its subdivisions is achieved, the main task of ICOMAQ will be to review the existing "wet" taxa of Soil taxonomy and to introduce new taxa where and when necessary. Such revised definitions will affect the work of other ICOMs dealing with aquic taxa in various orders, viz., Vertisols (ICOMERT), andisols (ICOMAND), and Oxisols (ICOMAX) -- including the aquic properties of plinthite occurring at shallow depths.

Specific related items for consideration that were proposed during the meeting include:

- characteristics of a cambic horizon in soils with an aquic regime;
- redefinition of Sulfaquepts, because the existing definitions are less than satisfactory for countries such as Thailand and Vietnam; and
- reexamination of the classification of sloping soils with an epiaquic regime; these soils, at present distinguished only at the

family level, may become separate epiaquic subgroups, if appropriate.

The revision of aquic taxa of Soil taxonomy should be based on factual data: profile descriptions, analytical data, and, where possible, measurements of the various parameters of the aquic regime just outlined. In most cases, simple field tests to determine degree of wetness and reduction at certain periods of the year may suffice.

CONCLUSION

Though the terms of reference of ICOMAQ are first and foremost taxonomic, the practical implications for activities such as those of INSFFER should be emphasized. A detailed knowledge of the soils is one of the more important parameters in the generalization of data from trials and their application to similar land conditions elsewhere. It is hoped that ICOMAQ will contribute to this knowledge.

CLOSING REMARKS

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I would evaluate the Workshop in a few words: good sequence of events!

The first part of the Workshop -- the presentation of papers -- gave us an overview, or state of the art of the main processes in and characteristics of wetlands, including the chemical, morphological, and soil fertility features peculiar under wetland conditions. A synthesis was made of the main problems encountered in the general classification of wetlands, followed by specific problems of certain classes of soils of worldwide occurrence, as well as particular problems at the national level such as those in Chile, China, Vietnam, and Zambia.

Then, the field tour, a representation of wet alluvial soils, mostly under rice, tested some of the propositions made in the papers and discovered new problems for soil classification (some management induced, such as puddling) and new criteria for interpreting the soils, especially for their use with rice. Here, the interaction of pedologists and soil fertility experts, sometimes with the participation of farmers, reached its maximum. Pedologists discussed different approaches in classification -- the Chinese, the Soviet Union, the German, FAO, and, primarily, Soil taxonomy. The tour was well coordinated, and I believe all gained something in the exchange.

Back at IRRI, the working groups synthesized the results obtained and recommended future work. I believe there is much assurance that most of the recommendations will be followed, having been addressed to active bodies such as ICOMAQ, INSFFER, and SMSS. The following are the two main outcomes, from my point of view:

1. International cooperation is producing agreements and improvements on many items of soil classification systems.
2. Interaction between soil classification specialists and experts in soil fertility, chemistry, physics, and management, in general, bring a better understanding of crop responses.

Both outcomes point toward improving the mechanisms and tools for agrotechnology transfer, in

the first case, through the soil or land units, and in the second, through integration of soil, weather, management, and crop performance.

Thanks are due to the administrators and scientific, and technical logistic personnel of the Bureau of Soils of the Philippine Ministry of Agriculture, IRRI, SMSS of USDA, and all the participants and the national institutions that allowed their participation and the success of this meeting.

Vo-Tong Xuan
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Whether you are a scientist in a developed or a developing country, your main concern is how to contribute to world efforts at solving the world food problems today and in the future. The means we are all concerned with is optimum land use for agricultural production: appropriate crops and appropriate packages of techniques on appropriate land. However, my experiences have shown that the solution is easy to state, but in practice difficult to achieve. In many developing countries, administrators from provincial to district levels have asked farmers and technicians to adapt on their farms the practices of good agricultural production from another place. Often we have heard it said that "IR42 can yield 8 t/ha in another province; we must therefore make it yield 8 t/ha in ours." The common mistake is to force the application of one technology without considering all the conditions required to make it succeed.

On the other hand, we also observe that crop and soil scientists do not always work together closely enough to supplement one another's efforts. Even among soil scientists, the pedologists often work separately from the soil fertility scientists! That is one of the reasons why, in the past, when we tried to compare INSFFER with IRTP results, we could hardly arrive at precise conclusions regarding the new technologies that should be recommended for transfer and where, when, and how they should be transferred. Most of the trials appeared to be carried out by scientists, most of whom did not care what was below the plow layer.

During the 1981 International Rice Research Conference (IRRC), the subject was site characterization of all IRTP and INSFFER experiments. And during the 1982 IRRC, Dr. Robert Brinkman and his colleagues presented a uniform procedure for site characterization to be adopted in IRTP and INSFFER programs. But until now it seems that many cooperating scientists, because of their weakness in pedology, and partly because they still do not appreciate the importance of site characterization, do not fully realize that procedure.

In developing countries such as Vietnam, an agricultural scientist involved in development work is often asked by farmers or local administrators for advice on "how to maximize present land resources." If this scientist wishes to be welcomed next time, he cannot say "Oh, I'm sorry. I don't know about that

because it's not my specialization." A developing-country scientist, therefore, should have broad-based training; and not be as narrowly specialized as a developed-country scientist. Particularly, the crop scientist should know not only his crop but also the soil where his crop can grow and how to conserve that soil's fertility to ensure optimum yield. Furthermore, he should know how to characterize that soil so that he can transfer the new technology to similar soils in other places. The pedologist should know not only his soil but also the species of the crop and the varieties within that crop that are likely to be planted, as well as the crop's requirements with respect to soil management, cropping systems, etc.

If we followed this workshop attentively we should have obtained sufficient knowledge on pedology and crop management. As a participant, I was fortunate to meet many distinguished pedologists and soil fertility experts from around the world and learn from their experiences. I have seen how they worked in the lecture room and in the field. I am glad to have taken the opportunity to discuss and share with them my knowledge and practical experiences in my own country. I am sure my colleagues from other developing countries, like me, appreciate this interaction. Overall, the workshop has been most rewarding. However, it could have been more meaningful if:

- the field tour included more sites to represent as many soil orders as possible, even though they do not occur at INSFFER sites;
- the lectures included some detailed introductions to Soil taxonomy. Of course, to the pedologists this may have been boring but it would have helped INSFFER soil fertility scientists understand and follow the discussions at the soil pits.

We have had a fruitful workshop. But the responsibility of a developing country pedologist does not end with the workshop. Rather, his responsibility starts when he returns home -- to gather his colleagues and to report to them what has been presented, to get them to understand the accepted knowledge and to put it into practice. Therefore, the more he is armed with detailed and well-illustrated information, the more successful he will be in transferring the knowledge. Hence the noble objectives of the workshop will be truly realized in the developing countries. Furthermore, I hope that through this workshop the INSFFER program within each cooperating country will be carried out more successfully. There should be a closer collaboration among pedologists and scientists involved in the INSFFER, IRTP, and Asian Cropping System Network in each national program.

On behalf of my colleagues and myself, I would like to congratulate the International Rice Research Institute, the Soil Management Support Services, and the Bureau of Soils for their joint efforts in organizing this very successful workshop. We thank them for their generosity in providing us this valuable opportunity to start working together.

Now that the workshop recommendations have been agreed upon, we face the challenge of realizing them through our respective organizations and respective programs.

A. M. Fagi
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It is indeed a great honor to be given an opportunity to speak during the closing ceremony of this workshop. To be fair, I incorporate all comments of my friends -- representative soil fertility scientists of the developing countries -- about the workshop, discussion, and site visit tour.

Pedologists, represented by Dr. Buol, define soil (in Soil genesis and classification, 1980) as a natural body, the property of which is influenced by soil-forming factors. Hans Jenny (in Factors of soil formation - A system of quantitative pedology, 1941) lists soil-forming factors as parent materials, topography, organisms, climate, and time. Man uses soil for crop production and has thus altered the factors of soil formation with time, resulting in various soil characteristics and, hence, soil classifications.

Graduate students majoring in soil fertility must understand that interrelationship. They are prepared to understand pedology and to appreciate the works of pedologists to be able to develop and modify the technology of soil, fertilizer, and crop management to help the farmers.

What happens when the soil fertility scientists return to their home countries? We have been busy with research that can immediately be used to benefit the poor. We will concentrate our work according to our profession or knowledge, that is soil fertility. A colorful soil map is just a decoration hanging on the wall of our room. Any differences or unexpected results of our study are just considered "due to chance" or "experimental error" -- very easy-going.

In a developing country, something impossible can be made possible within a short time. As an example, I would like to share with you our experience in Indonesia, of how we solved agricultural problems caused by the Mt. Galunggung eruption, just to show you how pedology or the work of pedologists should be appreciated.

Mt. Galunggung is located in West Java, 250 km southeast of the Sukamandi Research Institute. Its eruption took place continuously for 10 months (April 1982 through January 1983). It destroyed thousands of hectares of agricultural land; about 30,000 people were affected directly, and many more indirectly. In November 1982, while Mt. Galunggung was still ejecting volcanic materials, the government started planning for the rehabilitation of the lands to bring them back into production.

While geologists estimated that it might take 15-20 years to bring the destroyed lands back into production, we guaranteed that the lands could be planted immediately after the eruption ceased. Our pot experiments (which started while Mt. Galunggung was erupting) indicated that lava or volcanic ash could be planted to rice and secondary crops if the lava and the soil underneath were mixed. We observed in the fields that the topsoil and subsoil were fertile; every layer of the profile was fertile. When lava and the soil underneath were mixed in a certain proportion and fertilizers were applied at the rate that would bring the nutrient content of the mixture close to the original nutrient composition, food crops grew normally.

By using only these limited pot experiment data, a project called "Balebat Galunggung" or "Twilight of Galunggung" was initiated by the government in early 1983. It did work. Now, if you visit those areas, you will see rice and secondary crops growing prosperously within the ruins of houses and villages.

This workshop indeed benefits all of us. Soil fertility scientists appreciate pedology more than ever before, and much more can be done if we appreciate pedology. This does not mean that soil fertility scientists should be converted to pedologists; but it is most important that we work hand in hand in solving agricultural problems.

IRRI, SMSS, and the Philippine Bureau of Soils have made a very good start. Workshops and field trips of the type we just had should be encouraged. They will benefit the country where they are held, and thus better serve the poor of the developing nations.

For the benefit of both soil fertility scientists and pedologists, we would like to suggest that:

- the site visit tour or field trip be organized in such a way that all groups consist of both soil fertility scientists and pedologists, and that the number of participants in groups be reduced,
- a whole day of observation of the pits be followed by a discussion so that the participants can immediately exchange notes on what they have in their minds (strike while the iron is hot, so to speak),
- the results of Group A work be sent to us, together with the guide book, this will help us to understand more about pedology and better interpret the results of our soil fertility research.

Lastly, we would like to express our sincere thanks and appreciation to IRRI, SMSS, BS, and the organizing committee for giving us a chance to participate in this workshop. To the organizing committee, I would say that you have done an excellent job in making us more knowledgeable.

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It gives me great pleasure to say a few words in the name of soil fertility scientists.

First of all, I want to thank IRRI and the other institutions for organizing this workshop. Special thanks are due Dr. Greenland, Dr. Eswaran, Dr. De Datta, Dr. Raymundo, and all their coworkers. Each one of us realizes the immense work involved in ensuring the success of a gathering such as this one. Sincere congratulations!

Looking back, the conference showed a high scientific level; outstanding scientists from all over the world who have worked on wetland soils and rice crop gathered here and gave a solid platform for scientific discussions and exchange of experiences. Summarizing from the field of soil fertility and plant nutrition, even if much is already clear, there is still a dearth of knowledge of some chemical and biological processes in the soil-water interface such as the dynamics and transformation of macroelements and microelements, and nitrogen losses. In this respect, the conference gave many new ideas and approaches for further work.

The excursions were well planned, and the voluminous field book supplied us with a huge amount of data, which are more or less characteristic of the different sites. The excursions also gave us a very good chance to see the fascinating landscape and interesting countryside of the Philippines.

It was a good idea to mix soil taxonomy with soil fertility people; they learned from each other. And in that way, not only the sites but also the participants were classified, taxonomized, and fertilized completely according to the objectives of this workshop.

Finally, again, many thanks to all who have prepared this very effective symposium in such an excellent way and to the charming ladies who looked after us so nicely during the conference and the trip.

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