Quantifying the Effects of Land Conditions on Rice Growth

A case study in the Ebro Delta (Spain) using remote sensing

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Quantifying the Effects of Land Conditions on Rice Growth

A case study in the Ebro Delta (Spain) using remote sensing

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PROPOSITIONS

1. The yield of intensive rice production in a temperate climate, which is commonly determined by the grain number, can be maximized by having (i) a minimum plant number of 160-180 plants m^{-2} and (ii) a full canopy cover already at the panicle initiation stage. *This thesis.*

2. A compensatory relationship appears between the spikelet number and the grain size cancelling each other's variation. This implies that two cultivar-specific characteristic could be joined to form a rather stable variable, namely sink size, independent of cultivar type. *This thesis.*

3. Regression analysis indicates that the cation exchange capacity (CEC) of the topsoil is the most positively correlated soil factor with yield. The relation of CEC with soil texture is needed to obtain a translation to soil patterns in the field. *This thesis.*

4. In the Ebro Delta, it is the quality of the groundwater, in terms of its electrical conductivity, and not its depth that has significant effects on rice production. *This thesis.*
Rice grain yields increased in response to improved internal field drainage. Ramasamy, S., Ten Berge, H.F.M., Purushothaman, S., 1997. Field crops research 51, 65-82.

5. Shortage of zinc causes reduced rice growth in the Ebro Delta which contradicts the generally assumed shortage of nitrogen as being the prime reason for sub-optimal growth. *This thesis.*
Rice yield normally increases when the amount of nitrogen application is increased. Yoshida, S., 1981, Fundamentals of rice crop science.

6. Development of soil geographic databases is a powerful tool to enhance the necessary interdisciplinary approach in soil science. *King, D. and Le Bas, C., 1996, Soil databases to support sustainable development.*

7. The proper simulation of crop development and leaf area index, in conjunction with the carbon assimilation, is fundamental for a proper crop growth simulation model. *GCTE-START-WCRP report number 2, 1997, Workshop on climate variability, agricultural productivity and food security in the Asian Monsoon Region.*

8. The farmer perfectly understands that it is very risky to follow the guidance of those that do not have to suffer the consequences. *John Kenneth Galbraith, 1981, A life in our times.*

9. Science, politics and economy should be at the service of mankind and not mankind at the service of science, politics or economy. *Based on the Declaration of the World Summit for Social Development, Copenhagen, 1995.*

10. Why are we making such a mess? It is plainly not a question of resources as such. The world taken as a whole undoubtedly has the physical capacity, the wealth and the knowledge to cope with all its problems. *Alexander King, President Emeritus and co-founder of the Club of Rome, http://www.clubofrome.org.*

11. In science, as well as in real life, it is essential to differentiate between objectives and means.

12. The best part of the fieldwork is the shower afterwards!

Propositions associated with the Ph.D. thesis of David Casanova [David.Casanova@pobox.com]: Quantifying the effects of land conditions on rice growth: a case study in the Ebro Delta (Spain) using remote sensing.

Wageningen Agricultural University, May 6, 1998.

Abstract

This thesis represents detailed research on the "rice-soils-weather" system of the Ebro Delta (Spain) providing knowledge on how temperature, radiation, soil properties and farm management determine rice growth. After an introductory chapter, the findings are developed step-by-step. (i) Chapter 2 is an overview of the conditions in the study area. (ii) Chapter 3 focuses on the study of the soils creating a soil geographic database of the northern part of the Ebro Delta. Four properties were used for defining soil units; soil development, drainage status, texture and salinity. (iii) Chapters 4 and 5 deal with rice growth under weather limited conditions. Potential productions of 13000 kg ha^{-1} were estimated, while maximum yields of 11000 kg ha^{-1} were recorded at field level. In Chapter 4, the phenological development, the daily dry matter production and the leaf area development of the rice crop were modelled. In Chapter 5, the use of remote sensing techniques at field level for monitoring the rice crop status were tested. (iv) Chapters 6 and 7 analyse rice growth in relation to soil properties and farm management. Two soil factors were found to dominate the effects on yield: one was topsoil CEC (in strong association with clay content) with a positive effect, and the other one was soil salinity with a negative effect. High groundwater tables did not have significant effects on rice yield, except when the water had a high salt content. Four main groups of causes within the cropping status limited rice growth: potassium and zinc shortage where a strong antagonism of either factor with sodium was observed, low plant establishment where a minimum number of 160-180 plants m^{-2} was necessary to maximize yield, and length of the growing season, especially the length of the pre-heading period in which the potential size of the crop was primarily determined. Potassium and zinc shortages in the plant were mainly induced by soil salinity. High K in saline soils did not increase K uptake. It remains to be determined if addition of Zn will increase Zn uptake. Information on environmental conditions of the study area and data on rice cropping is presented so that farmers, extension workers and decision-makers find themselves in a better position to adapt their management and policy making. This thesis intends to support development of decision systems and to increase cooperation between agricultural and environmental scientists focusing on concerns of society.

Preface

This work is closely connected with my personal history. On account of the nature of my father's occupation, a rice farmer, I have always been in close contact with the Ebro Delta environment. Since my early childhood I have heard expressions such as: "this is a good soil" or "in such land you better bring cows to eat the grass/weeds", or "the salinity is going to eat us", or "these office people know nothing about rice". On the other hand, at university classes, at government offices and listening to discussions of so-called wise people, I used to hear: "these people from the Ebro Delta are uncivilized", or "farmers are intrinsically dumb, because we teach them their everyday work", or "the delta is beautiful; birds, coast, lakes, flora, bad there are farmers". Additionally, between farmers, experimental stations, Universities, research institutes, etc., criticism is leveled against each other for being too theoretical, too burocratic, too silly, too -you name it-! Hence, I have always wondered: (i) what kind of instinct makes us think that we are better, or do better, or know more than others?, why can't we make an effort to understand others and their ways of expression? (ii) Why things happen like they happen?, what makes one soil be better than another?, what is the origin of those "devilish" soil properties, how do they affect rice growth? (iii) Alternatives: aren't there other ways of living, of farming, of doing things?, or do we have the exclusivity! Things are not intrinsically better because they have always been like this. We should be able to select the good from the past, work in the present, and hope for a better future!

This research project has tried to bring together some "homogeneity in diversity" within this environment: Working in farmer's experimental farms, in consultation with the experimental station of the Ebro Delta, collaborating with the soil section of the Generalitat de Catalunya and the University of Lleida, and the cooperation of the Institute of Earth Sciences in Barcelona and the Wageningen Agricultural University. Another key matter that I have learnt during these years is that: "In life, you cannot do much on your own"! Furthermore, in nature things are not directly "white or black"! Thus with the goal of understanding the environmental relations and their interrelations, different disciplines have been brought to bear fruit: soil science, simulation models, rice physiology, remote sensing, GIS, statistics. Thus, an incredibly large number of people from diverse backgrounds has contributed to this thesis. This research project could have only been achieved with an inter-disciplinary framework of discussion, intercommunication, and settling of ideas and methodologies. Furthermore, long, extremely long journeys along the Ebro Delta-Lleida-Barcelona-Wageningen roads and crossroads were necessary.

I start thanking my promotor (at Theoretical Production Ecology) Jan Goudriaan for transmitting his enthusiasm to observe nature, to understand natural processes, to trust in field data, and to be simple in terms of modelling plant growth and of personal attitudes towards life. Even drinking wine on the beach under a full moon was a simple, educational and grateful experience! I thank my promotor (at Soil Science and Geology) Johan Bouma for his thorough comments over my writings and his sharp criticisms with "the right word at the right place at the right time". Johan always encouraged me to keep on going, never a stop-hand, with a cheering up attitude. I also owe many thanks to my co-promotor Gerrit Epema for being my "liaison officer" in Wageningen and for trying to teach me to be direct and specific!

Quiero agradecer al Consejo Superior de Investigaciones Científicas, al Instituto de Ciencias de la Tierra "Jaume Almera" y en concreto al Dr. Luis Solé, el soporte recibido. Les estoy muy agradecido por la confianza depositada en mí, facilitándome desde una beca al principio del proyecto hasta un contrato al final para poder realizar esta publicación con el tiempo y medios necesarios.

A la Universitat de Lleida, a l'Escola Tècnica Superior d'Enginyers Agrònoms i en concret al departament de Medi Ambient i Ciències del Sòl, estic molt agraït per la seva col·laboració amb aquest estudi. Al Prof. Dr. Jaume Porta per haver-me obert les portes a col·laborar, i especialment a l'Angela Bosch per haver estat la "liaison officer" a Lleida. Sempre he trobat en ella amabilitat, empatia i un somriure.
Voldria agraïr a la Secció d'Avaluació de Recursos i Noves Tecnologies del Departament d'Agricultura Ramaderia i Pesca (DARP), especialment a en Jaume Boixadera, la seva inestimable col·laboració en la prospecció i caracterització dels sòls. En aquests moments vull recordar l'amabilitat i servicialitat d'en Josep Llop durant totes les hores passades conjuntament fent sondejos en la polseguera de l'hivern. Josep, gràcies; no és només "lo forat, la textura, i cuatre fartaneres" que hem compartit aquests hiverns al Delta!

My thanks and gratitude to the former trainees that supported long hours of walking in the mud, windheadache, soil and plant sampling and particularly *counting* "plants, panicles, grains, unfilled grains, -counting, counting, and more counting-": (i) Chris Varekamp, Menno Schepel and Wannarattana Janyarunguang (Ms. Nok) from Wageningen Agricultural University; (ii) Xavi Gerrós, Daniel Martinez and Jordi Rebull from the University of Lleida.
All colleagues who contributed in one way or another to this work, are kindly acknowledged. Agradezco a todos los compañeros que han contribuido de una forma u otra a la realización de este trabajo. Agraeïxo a tots els companys que han contribuït d'una forma o altra a la realització d'aquest treball.

- At Soil Science and Geology, WAU, especial consideration goes to Thea's efficiency, Andrea's accordeon, Marcel's software, ...,!
- At Theoretical Production Ecology, WAU, I have always felt accompanied. Special consideration goes to Bjorn Dirks, Joost Wolf, Gon van Laar, Marcos Bernardes, Daniel Rodriguez, Fernanda Dreccer and others, for being always there: for commenting at professional and personal level, for faxing articles, for having dinners and coffees, for ..... Thanks also to Jacques Withagen for his help with statistics, something both useful and difficult!
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- A la Montse, l'Asún, en Francesc, en Rafa, en Joserra, ..., del Departament de Sòls i Medi Ambient de la Univeristat de Lleida per les llarges jornades passades junts durant varis estius.
- A la secció de cultius i genètica del Departament de Producció Vegetal i Ciència Forestal de la Universitat de Lleida per haver facilitat la instrumentació per la realització de diferents mesures en camp i laboratori.
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- A Figares, Benito, Joaquin de Cantamanyanes, Claudio i Sisquet de la "Cooperativa de Regants" per la seva col·laboració en la cartografia dels sòls.
- A l'Institut Cartogràfic de Catalunya per proveir imatges de satèl·lit.

El comienzo de cualquier investigación conlleva dudas, estímulos, fracasos, aglomeración de ideas. Las personas necesitamos de "trampolines" que nos empujen hacia arriba. Guardo un recuerdo muy especial de esa primera etapa, -cuando aún no tienes claro qué hacer y cómo hacerlo-, del Dr. Ir. Julián Martínez Beltrán (FAO), and of Ir. Dick Legger (WAU); Geen Alles Goed, maar Alles Prima!

Furthermore, I would like to thank the Commission of the European Communities for funding this project (ERB-4001-GT- 931494 / 964205) and the Global Change and Terrestrial Ecosystems (of the International Geosphere and Biosphere Programme) for accepting this particular project as part of the "Rice Network" and of the Core Research Programme, Category 1 (cf. pp. 80-81 of the GCTE Operational Plan). The soil database developed in Chapter 3 is also part of the general Soil Survey of Catalonia that is being generated by the Catalan Autonomous Government.

Although all of the above-mentioned people encouraged me to work in this project with all my energies, I would have never been able to finish this thesis successfully without the constant and faithful support of my mother, my brother, all my family and very especially the presence in my life of my wife, Blanca. There are also many other people that have had a strong impact in my life. These people are not mentioned here and many of them are unknown, forgotten of History, however I am what I am thanks to all of them. So, thanks to all these NOBODIES I've met who taught me to dream, smile, cry, think, laugh, read, discern, write, feel, love, share, ..., THANKS-GRACIAS-MERCÈS-DANK U WEL!

The Nobodies

- They are not, although they are.
- They do not speak languages, but dialects.
- They do not practice religions, but superstitions.
- They do not make art, but folklore.
- They are not human beings, but human resources.
- They do not have faces, but arms.
- They do not have a name, but a number.
- They do not appear in the Universal History,
  but in the crime sheets of the local papers.

The nobodies, that are worth less than the bullet that kills them.

Los Nadies

- Que no son aunque sean.
- Que no hablan idiomas, sino dialectos.
- Que no practican religiones, sino supersticiones.
- Que no hacen arte, sino folklore.
- Que no son seres humanos, sino recursos humanos.
- Que no tienen cara, sino brazos.
- Que no tienen nombre, sino número.
- Que no figuran en la Historia Universal,
  sino en la crónica roja de la prensa local.

Los nadies, que cuestan menos que la bala que los mata.

(Eduardo Galeano, "El libro de los abrazos")

Contents

Account

Part of this thesis have been included, in part or in whole, in the following publications:

Chapter 3 Casanova, D., Boixadera, J., Llop, J.. Development and applications of a soil geographic database in a deltaic environment under rice cultivation. *Arid Soil Research and Rehabilitation,* submitted.

Chapter 4 Casanova, D., Goudriaan, J., Bosch, A.. Testing the performance of ORYZA1, an explanatory model for rice growth simulation, for Mediterranean conditions (Ebro Delta, Spain). *European Journal of Agronomy,* accepted.

Chapter 5 Casanova, D., Epema, G.F. and Goudriaan, J.. Monitoring rice reflectance at field level for estimating biomass and LAI. *Field Crops Research, (1998) 55: 83-92.*

Chapter 6 Casanova, D., Goudriaan, J., Bouma, J., Epema, G.F.. Yield gap analysis in relation to soil properties in direct-seeded flooded rice. *Geoderma,* accepted.

Chapter 7 Casanova, D., Goudriaan, J., Catala Forner, M.M., Withagen, J.C.M.. Quantitative analysis of yield and its determining factors in direct-seeded flooded rice. *Field Crops Research*, submitted.

General introduction

1.1. SETTING THE SCENE

This thesis intends to move beyond the classical approach where an often rather remote problem is identified, and where materials and methods are carefully described to allow punctual experimentation resulting in results and conclusions that are scientifically acceptable. In this study, we focus on a large area of land that used to be an unhealthy swamp until recently. Within a relatively short period, this area has been transformed into a productive rice-growing area where interests of nature are to be respected. Still, the potential of the area has not yet been reached and the major objective of this study is to unravel the basic soil and plant processes, so as to derive ways and means to further improve the agricultural production system in a sustainable manner. Thus, state-of-the-art modern technology is mobilized, but only in as much as it can help to improve our understanding, not as a scientific objective in itself. Overall, intensive contacts have been maintained with the "stakeholders", the farmers of the area, to safeguard future application in practice of insights gained in this work.

Rice is cultivated throughout the world in many different ways and degrees of intensity. Basic differences exist between the cultivation of upland and lowland rice. Lowland rice may be irrigated or rainfed. Under fully irrigated conditions, rice may be transplanted or directly seeded. Direct seeding under full irrigation is the most common practice in Europe, Australia and the USA. This thesis presents a quantitative analysis of fully irrigated direct-seeded rice growth and its relation to soil and weather conditions in the Ebro Delta in Spain.

1.2. RICE IN THE EUROPEAN UNION

Rice is cultivated in a wide range of ecological environments in all the continents. As an example, it is cultivated at 53° north in north-eastern China, at the equator in Bolivia and at 35° south in New South Wales (Australia). It is grown below sea level in Kerala (India); at or near sea level in most rice-growing areas; and at 1800 m in Madagascar or at 2400 m in Nepal. The world rice surface is around 150 million hectares with an annual production of 550 million tons of paddy rice (FAO, 1995). The production in the European Union (EU) of paddy rice in 1997 was 2.7 MT, on approximately 434.000 ha of rice cropland (http:www.fao.org).

The principal characteristics of the rice market in the EU are:

- A production localized in the south of the EU (Fig 1.1),
- A demand for quality, promoting a high diversity of cultivars (Birot, 1995).

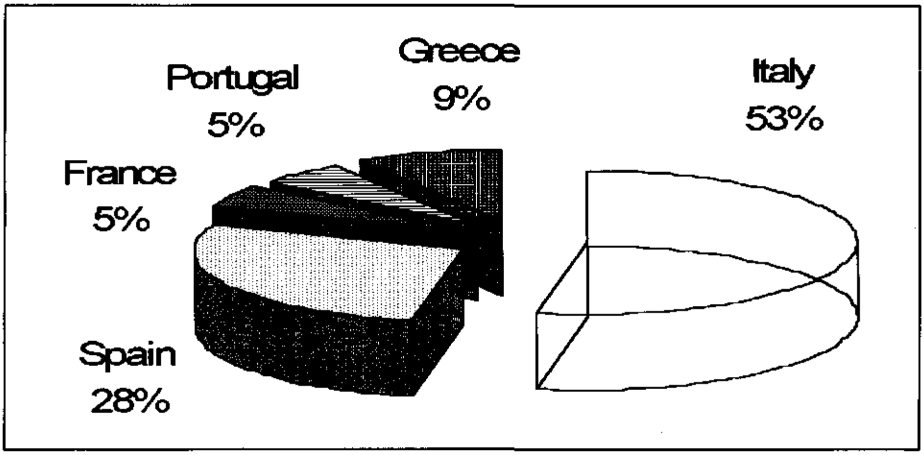

Fig. 1.1. Paddy rice production in the European Union in 1997 (source: http:www.fao.org).

Rice is the only cereal consumed as full grains, and its visual and taste quality is directly perceptible for the consumer. Before consumption the rice grains must be separated from their hull (shell). This transformation from paddy rice to white rice gives losses of approximately 40%. The commercial classification of rice is based mainly on the shape and hardness of the white grains (see Table 1.1). The rice of Japonica origin is mainly wide and short in contrast to the Indica-type which is narrow and long (Faure and Mazaud, 1995). The first is produced traditionally in temperate climate and the second in tropical climates (http:www.cgiar.org/irri). Within this classification, each cultivar has its own plant and grain characteristics.

Table 1.1. Commercial classification of rice in the European Union based on white grains.

	Japonica				Indica
Grain characteristics	Round	Medium	Long A	Long B	
Length (mm)	< 5.2	< 6.0	> 6.0	> 6.0	> 6.6
Ratio of Length to Width			< 3.0	> 3.0	> 3.0
Examples of Cultivars	Bahia,	Lido,	Ariete,	L-202 (Thaibonnet)	IR 8
	Tebre,	M-202 (Thainato)	Koral,		IR 72
	Senia		Drago		

In the EU, the actual white rice production is 1.6 MT and the consumption is 1.9 MT (FAO, 1995). This leaves a small margin for import that the new World Trade Organization agreements will further facilitate (Fig. 1.2). In southern-Europe, people mainly prefer round, medium and long-A grain rice because of culinary tradition such as *paella* in Spain or *risotto* in Italy. These cultivars are sticky on cooking and remain soft after cooling because of a high water absorption (http:agronomy.ucdavis.edu/ricestation; Aliaga, 1984). In contrast, long-B and Indica rice is often cooked in high quantities of water without bulking (swelling) and stays fluffy. In northern-Europe, the demand of the market is oriented towards the long-grain rice because of a more recent culinary habit derived from abroad (Chataignier, 1994).

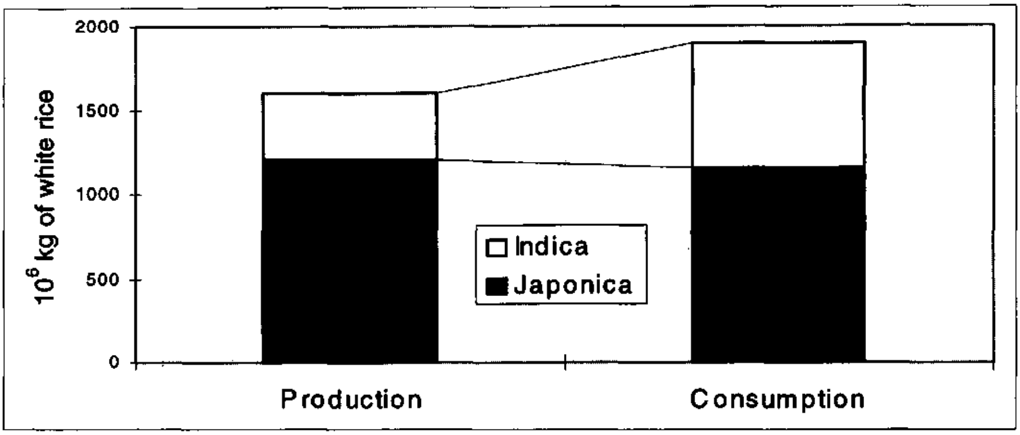

Fig. 1.2. Production and consumption of the two main rice types in the European Union.

1.3. RICE IN THE EBRO DELTA

The Ebro Delta is an important aquatic environment in the western Mediterranean. It occupies an area of 32000 ha, from which approx. 24500 ha is cultivated, divided in a northern side (left bank) and a southern side (right bank) of the river. At present, the Delta is occupied by 46.000 inhabitants and is of considerable importance in agricultural terms as it yields 12% of the total production in Catalonia. Additionally, it plays a key role as a nature reserve with over 500 recorded flora species, an extensive range of entomological fauna and its internationally important 300 bird species (60% of all the European species). At the request of the inhabitants, the "Ebro Delta Natural Park" was established in 1983 to preserve and improve the natural inheritance. Since then, a part of the Ebro Delta is considered natural park (Table 1.2) and the rest of the area is also affected by the park, as it restricts agricultural activities in adjacent land. Striking a balance between the ecological and agricultural value of the Ebro Delta is not an easy task!

Table 1.2. Distribution in hectares of the Ebro Delta (as in June 1996).

	Left Bank	Right Bank	Total
Natural Park	2099	5703	7802
Other areas	10079	14178	24257
Total	12178	19881	32059

The land-use system of the Ebro Delta is determined by specific land characteristics, and environmental and market factors. Wetland rice cultivation is spread over the major part of the Ebro Delta, 86% of the cultivated area in 1996. Wetland rice presents a high interest nowadays as it is one of the few crops without surplus within the EU. Interest is also generated by the agricultural trend to reduce high inputs, that are associated with more intensive crops, in order to preserve the environment and by the dynamics of the rice fields which are beneficial for maintaining the ecological balance of the wetlands (Regulation 1765/92 of the EU).

Rice yields are extremely variable and suboptimal, although the farming system is highly mechanized and most modern technologies are used. Under present conditions one rice crop per year is harvested, yielding, on average, slightly more than 6 tons per hectare of paddy rice (14% moisture). Based on existing rice growth models, potential production estimates of 13 tons ha^{-1} are simulated. The actual minimum and maximum recorded yield varies from 3 to 11 tons ha^{-1}. Hence, a gap exists between the potential and maximum actual yield. Furthermore, there is a high variability in rice growth and yields. The reason for such discrepancies is the unbalance between:

(i) land characteristics (supply side). The irrigation water is of good quality. The amount of fertilizers, fungicides, etc., used by the farmers is ample. Soil data, however, were not available and recommendations did not differ from one area to the next. Farming practices are in general based on "what the neighbour does", but soil properties differ very much. Thus, for example, coastal sandy soils are managed similarly as peat soils.

(ii) rice requirements (demand side). Rice is a unique crop for various reasons, but in particular because it is grown under a continuous flow of irrigation water (nowadays on average, 4000 litres of water are used per kg of rice produced). The requirements of the rice plant had to be defined; first in terms of weather conditions (temperature and radiation) and after that in terms of farm management (tillage, plant establishment, etc.) and soil conditions (nutrients, etc.).

The general objective of this thesis is to understand the "rice-soil-weather" system in the study area. Why is monocultivation of rice the major type of land-use? How does rice grow and develop? What is the maximum production in the Ebro Delta? Soil qualities usually involve a physical component such as water transport. If no water limitation exists in paddy fields; which soil properties are limiting and how does this affect rice growth (e.g. do they induce a nitrogen or a zinc shortage or a ..., do they reduce the number of grains, or the weight of the grains or ...)?

The general objective can be divided in the following specific objectives:

(1) To determine key soil properties and their spatial distribution, to understand the soil-functioning processes, and to create a soil geographic database.

(2) To determine the optimal growth curve for a rice crop based on weather (temperature and radiation) under no "soil-related" limitation. In technical terms, to assess the potential production growth curve.
(3) To determine the interrelation between soil properties and rice growth. The aim is to understand "which & how" soil properties are affecting rice growth. In simple terms, identify *which* soil properties contribute to the yield-gap between potential and actual production. Understand *how* soil properties are affecting the crop status which at the end of the "causal chain" determines yield.

1.4. OUTLINE OF THIS THESIS

For achieving the objectives described above, a wide range of methodologies has been used. From simple measurements of plants per unit area using a children "hula-hoop", to laboratory analyses, electromagnetic induction and remote sensing measurements. For each chapter, depending on its objective, field measurement techniques were adapted based on common sense obtaining a maximum of information at minimal cost. Measuring and quantifying was not an objective in itself, it is just a crucial way to describe the soil-plant system in a universally valid and reproducible manner.
The structure of this thesis is illustrated in Fig. 1.3. As we are dealing with reality and its conflicts, first we have to get a clear view of the settings in the Ebro Delta. In Chapter 2, three important features of the study area are discussed; (i) the climate, water resources and geomorphology because of its relevancy to the land concept, (ii) the socio-economic basis, and (iii) the rice production system.

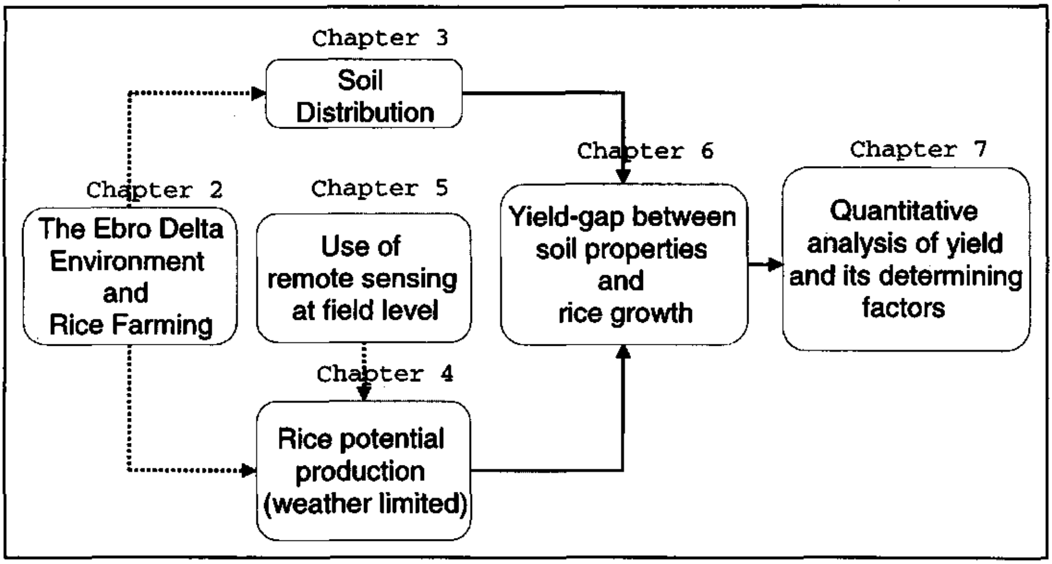

Fig. 1.3. Outline of the thesis.

"We can't make cheese if there is no milk". This statement is the starting-point of the experimental research of this thesis. Obviously, the first need of such a project is to know which soil units and properties are encountered in the study area. Chapter 3 examines the soil types, the main soil properties and their distribution in the northern part of the Ebro Delta (left bank). All data were stored in a soil geographic database or a soil information system.

The second need is to know what are the rice requirements under no soil limitations, or in other words, what is the maximum production just limited by weather conditions. Crop yields have an upper boundary which is determined by temperature and radiation. Chapter 4 provides the answer to this question and an "ideal" growth curve is defined. Two common rice cultivars in the "best farmers" scenarios are monitored in detail: a traditional short-grain cultivar, Tebre, and a recently introduced long-grain cultivar, L-202. The yield gap between potential production and the maximum monitored yield is identified. The objective is not to model rice growth in itself, but to understand the rice plant's life cycle under optimal conditions.

In agriculture, monitoring of crop growth and early estimates of final yield are of general interest. Individual farmers may want to know their rice crop status at any time for optimum management. Consequently, Chapter 5 deals with estimation of the rice crop status (biomass and leaf area index) just by monitoring its reflectance at field level. With a hand-held radiometer, so-called temporal signatures of the rice crop were obtained. These reflectance values are converted to fractions of intercepted photosynthetically active radiation (PAR), f_{PAR}. From f_{PAR} it is rather simple to estimate rice biomass or leaf area index. The innovative aspect is that it is a simple, fast and non-destructive method to measure crop status at field level.

The answer to the third and last specific objective, or the final integration between rice and soil conditions is achieved in Chapters 6 and 7. Chapter 6 identifies and quantifies *which* are the main soil properties limiting rice production, while Chapter 7 goes into *how* are they limiting. A total of 50 fields spread along the Ebro Delta were selected during the 1995 and 1996 rice growing campaigns. Soil units were identified and topsoil properties were measured. Rice growth was monitored and final yield recorded. Finally we analysed which factors determined yield and how they did. For example, if one field had lower production than another, was it: (i) because the one had a bigger leaf area (a matter of source limitation) or (ii) it had a similar leaf area but with a higher number of spikelets (a matter of sink limitation). Furthermore, maybe soil salinity had effects on lowering the germination of the crop and therefore on the leaf area index, while a poor drainage condition could have effects on reducing the percentage of filled spikelets. Or maybe it was the other way around?

Chapter 8 presents a general and integrated discussion of the project, extending its view to other rice growing areas in the temperate climate. Research has shown that there is a big gap between what is potentially possible and what is achieved. Some farmers do well, however! We explored the "best-farmers" scenario. We compared and analysed yield differences between "good/bad farmers" and "good/bad soils". This thesis offers the potential to move beyond just random experimental work. Future research should be oriented towards developing decision support systems for agricultural and environmental management at the major land units, combining soils in a geological, hydrological and climatic setting. *What* to do *when* is the major question. In what ways are soils functionally different? Future farmers and decision-makers should have the necessary tools for deciding themselves what to do based on a thorough knowledge of the area and its natural processes.

The Ebro Delta: Its environment and its rice production system

Abstract:
The Ebro Delta as it protrudes into the Mediterranean sea has been largely formed by sedimentation. This chapter reviews its environmental conditions: climate, water resources and geomorphology. Rice farming is the prevailing agricultural activity in the Ebro Delta. The characteristics of rice farming in the area are presented. Its relative importance in relation to other forms of agronomy and economic activities is briefly discussed.

2.1. THE ENVIRONMENTAL CONDITIONS OF THE EBRO DELTA

The Ebro Delta is located in the north-east of Spain. It protrudes as a lobe of some 32,000 hectares into the Mediterranean sea (Fig. 2.1). Its inland margin trends NNE-SSW for about 20 kilometres and marks the position of an old shoreline, whilst its mouth lies some 25 kilometres seawards.

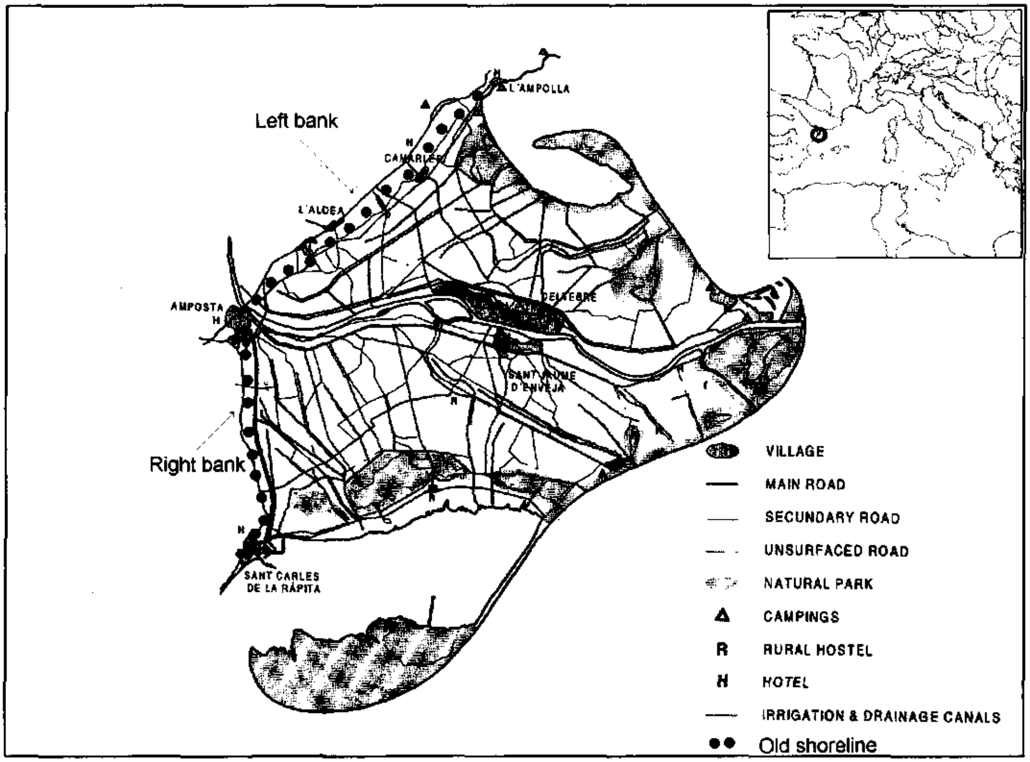

Fig. 2.1. General map of the Ebro Delta (source: Generalitat de Catalunya).

2.1.1. Climate

The climate in the study area is typical Mediterranean (*Csa* according to the Köppen classification) with mild winters and warm, but not torrid, summers. Rainfall averages 530 mm, and the annual potential evaporation amounts to about 1200 mm. There is a total mean hydric surplus of 20 mm during October, November and December and a total mean hydric deficit of 690 mm during the remaining part of the year. Relative humidity is very constant all through the year. Daily average values of relative humidity are 80 percent (from 1992 to 1996). Temperature fluctuates from a monthly average of 25°C in July-August to 9°C in January-February, with very seldom night frosts. Figure 2.2 shows weekly averaged temperature and global radiation in 1996.

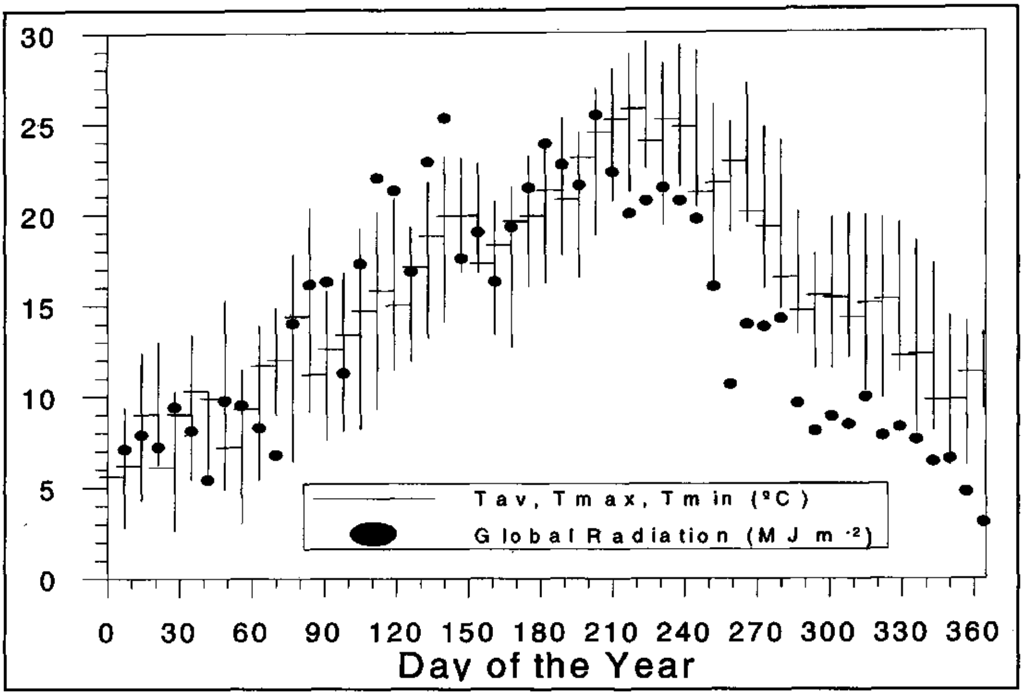

Fig. 2.2. Temperature and global radiation weekly averaged on the Ebro Delta in 1996.

The tidal range is small, with a maximum of ±0.40 m. However, during periods of strong northern ("vent de dalt") or eastern ("llevant") winds in April-May and September-October, the sea level may rise by 1 m.

2.1.2. Topography

The delta area is very flat and its maximum height above the sea is 4.5 m at Amposta, where the Ebro river emerges from the uplands. The whole landscape has a man-made look, however the slight differences in topography are important for distinguishing depositional environments and soil properties. Generally the level of the river levees is at about 3 m and the topography gradually slopes to sea level along a south-eastern direction for the right bank and north-eastern direction for the left bank. These slopes are in general of the order of 0.01% to 0.02%. About 10 percent of the delta area is at a level above 2 m (natural levees along the river and near the inland hills); 30 percent between 1 m and 2 m; 60 percent below 1 m; and limited areas (such as lagoons) are even below average sea level. A digital elevation model (DEM) of the left bank of the Ebro Delta is provided with the soil geographic database of Chapter 3. A topographical map from the DEM generated by interpolation procedures is included in Chapter 3 as Plate 3.3.

2.1.3. Water resources

The Ebro drains the greater part of the southern slopes of the Pyrenees. It travels 928 km from its origin to its mouth. It drains a catchment of 84,230 km^2 (17% of Spain). Figure 2.3 illustrates the average water discharge of the Ebro river in comparison with other rivers of Europe.

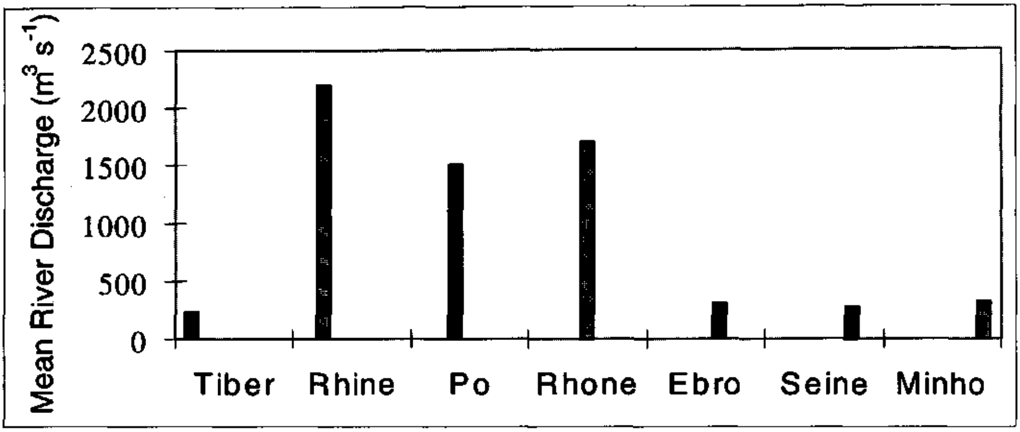

Fig. 2.3. Mean discharge from 1986 to 1995 in various European rivers.

The average discharge over the last 10 years is 300 $m^3 s^{-1}$ (Consorci d'Aigües de Tarragona, 1991). Figure 2.4 illustrates the monthly discharge and water conductivity in Tortosa (35 km inland of the river mouth). The river water is of good quality for irrigation; below 1.5 dS m^{-1} during the year.

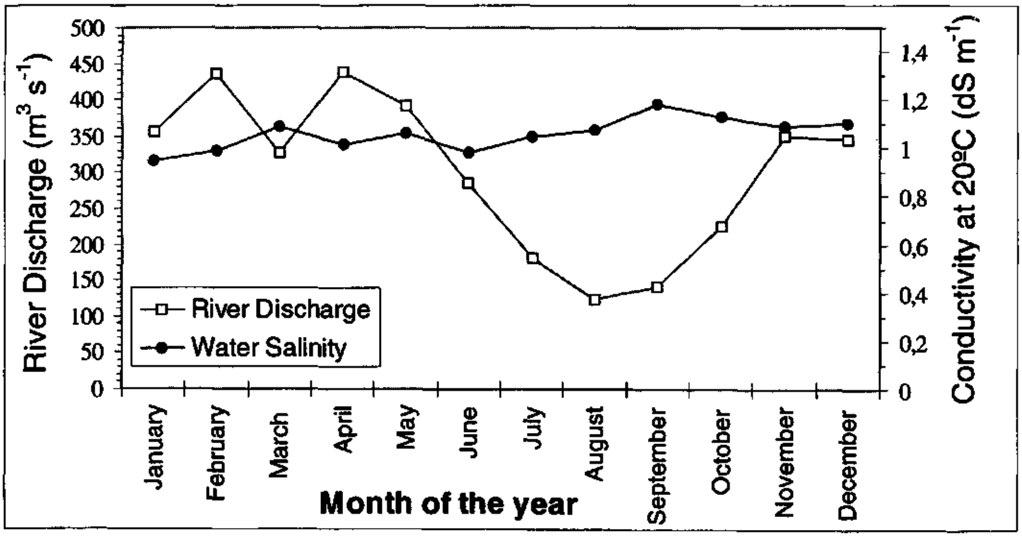

Fig. 2.4. Monthly river discharge and water conductivity averaged from 1986 to 1995 in the Ebro Delta in Tortosa.

A detailed analysis of water (Canicio, 1996) from the irrigation channel and a spring located in the Delta is presented in Fig. 2.5. Essentially the water from the river has higher sodium, chloride and sulfate content than the water from the spring.

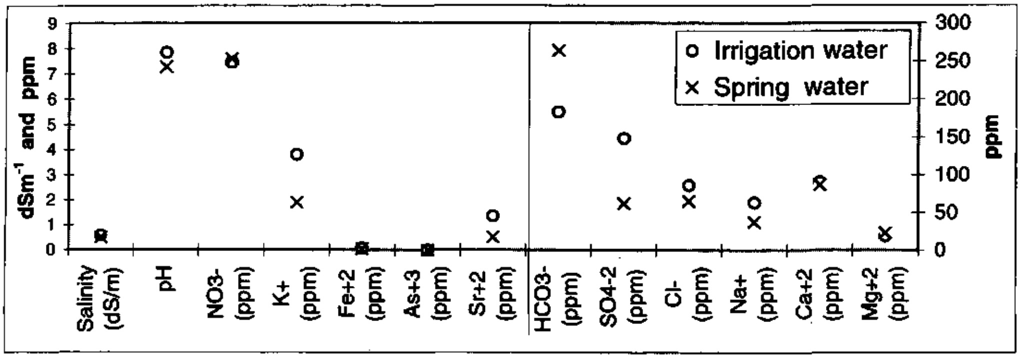

Fig. 2.5. Water analysis (April of 1994) of an irrigation channel and a water spring in the transition zone between the adjacent uplands and the deltaic plain.

2.1.4. Hydrogeology

When farmers cultivate rice, they use large amounts of fresh irrigation water in order to control salinization. The fresh irrigation water prevents capillary rise of the saline groundwater. The groundwater level in the area is high. Before irrigation in April, the groundwater is below sea level over most of the area. The groundwater rises rapidly with irrigation. In September, it is between 0 and 30 cm from the surface on large parts of the Delta. After irrigation and the rainy period in autumn, the groundwater level lowers. This high groundwater level is due to the absence of a gradient or natural drainage that would facilitate discharge to the sea (Bayó et al., 1992, 1997). The groundwater was originally trapped during the deltaic evolution and has been renewed by irrigation, rainfall and seepage losses (Loaso and Herrán, 1989). This groundwater is highly salty, sometimes more than sea water. Over extensive areas the groundwater electrical conductivity at 5 m depth varies from 16 to 60 dS m^{-1} with maximum values of over 100 dS m^{-1} (López Gutierrez, 1996). Chapter 3 shows chemical analysis of the groundwater at various sites and its relation to soil properties.

2.1.5. Stratigraphic framework

The geology of the Ebro Delta is detailed in the Spanish geological map 1:50.000, (IGME, 1979; sheets 522 and 523). There is a very thick sedimentary sequence (up to 70 m under the river mouth) formed in the Holocene period. The major sedimentary units beneath the Ebro Delta are shown in Fig. 2.6.

The *substratum* of the delta complex formed by Pleistocene deposits, with good surface permeability, consisting mainly of fluvial gravels and piedmont deposits.

Coastal plain lutites (fine deposits) of paludal and fluvial origin from when the sea level was low.

Beach and nearshore sands and gravels formed during the rise in the sea level.

Offshore marine clays characterized by high content of marine fauna and low of terrigenous matter. They are mainly in the east because, at that time, westwards was the beach. They are equivalent to the present outer shelf deposits.

From here on, the sequence of deposits relates to the progradation of the Delta.

Prodeltaic deposits (silt and clay) formed in the deep water while the Delta was moving outwards. They have, however, scarce or almost nonexistent marine fauna. These deposits have on average 10 m thickness in the eastern part of the Delta with a progressive reduction in thickness westwards.

Prodeltaic deposits (sands of beach and nearshore). They form a layer extending beneath all the deltaic plain of fluviomarine and holomarine sands, 10 m thick on average, which can, however, range between 1-20 m.

As the Delta prograded seawards; the river course lengthened, the river meandered across the top of the Delta depositing meander belts of *fluvial sand-silt sediments* in the channel whilst at the same time *paludal fine sediments* deposited in the overbank floodplains.

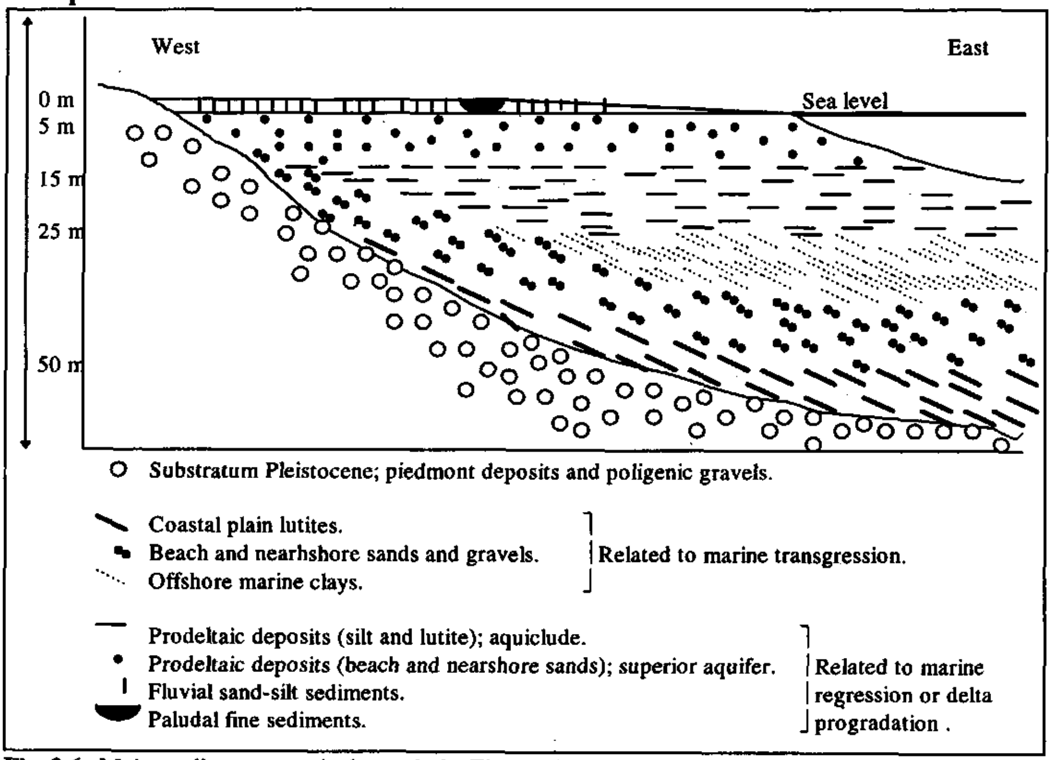

Fig. 2.6. Major sedimentary units beneath the Ebro Delta (after Maldonado, 1972).

The conglomerate of the foothills dips towards the east and is covered by the virtually impervious prodelta clay increasing in thickness towards the east and diminishing towards the foothill. This impervious stratum is absent in places along the western boundary of the Delta. There, fresh water comes to the surface both as seepage water and in springs ("ullals"), originating from the conglomerate that acts as aquifer and is not sealed by the aquiclude of prodelta clay. In this area, peat has developed, especially in the southern part of the Delta.

2.1.6. Deltaic Evolution

The development of the Ebro Delta began approximately 20.000 years ago at the end of the last glacial stage. During the first 12.000 years, the rise in sea level predominated. Thin *transgressive sequences*, from 90 to 10 m below present sea level, were developed as the sediments borne by the river were reworked by waves. During the last 8.000 years sedimentation predominated. These sediments are characterized by the upward increase in grain size and decrease in fauna, and form the so-called *offlap or coarsening-upward sequences*. The Delta, at that time, prograded from 10 m below to actual sea level (Maldonado, 1975). Above present sea level, most of the sediments are of fluvial origin. In the process of infilling of the lacustrine environments and abandoned courses, *fining-upward sequences* develop. Subsidence or compactation effects are and have been influencing the deltaic sedimentation. Other important factors which should be considered, e.g. a man-induced decrease of the river discharge and even more important, the processes of distributary diversion. Moreover, the erosion of abandoned lobate deltas provides sediment, for the development of beaches and nearshore spits.

Figure 2.7 shows the evolution during the last 4.000 years of the Ebro Delta, (Canicio, 1996). The deltaic plain consists of three pronounced delta lobes. The development of two of these lobes has notably increased the deltaic plain surface area during the past four centuries. According to Kleinpenning (1969), Amposta was an open sea fishing harbor during the 15th century. Then, however, the Delta suddenly began to develop quite rapidly. This was a consequence of the increasing deforestation in the Ebro Basin, which caused the river Ebro and its tributaries to transport increasing quantities of sediments. The southern Delta lobe is the oldest, growing until nearly the 16th century. The northern lobe mainly developed throughout the 17th and 18th centuries, and the early 19th century. The active period of the central Delta lobe coexisted with that of the northern Delta lobe during its final stage of development. Initially the central Delta lobe had a northern distributary active throughout the early 18th century. The eastern distributary reached its maximum development about 1946. A major flood in 1937 resulted in a fourth lobe when a new channel broke through one of the existing lobes. This channel diversion resulted in a new river mouth and the abandonment of the older one by 1957 (Maldonado and Riba, 1971). The present development of the Ebro Delta is controlled by the diverted channel to the north and the decrease in the river discharge over the last decades. The present sediment load is about 1% of 100 years ago due to dam construction throughout the catchment area (Guillén and Palanques, 1992).

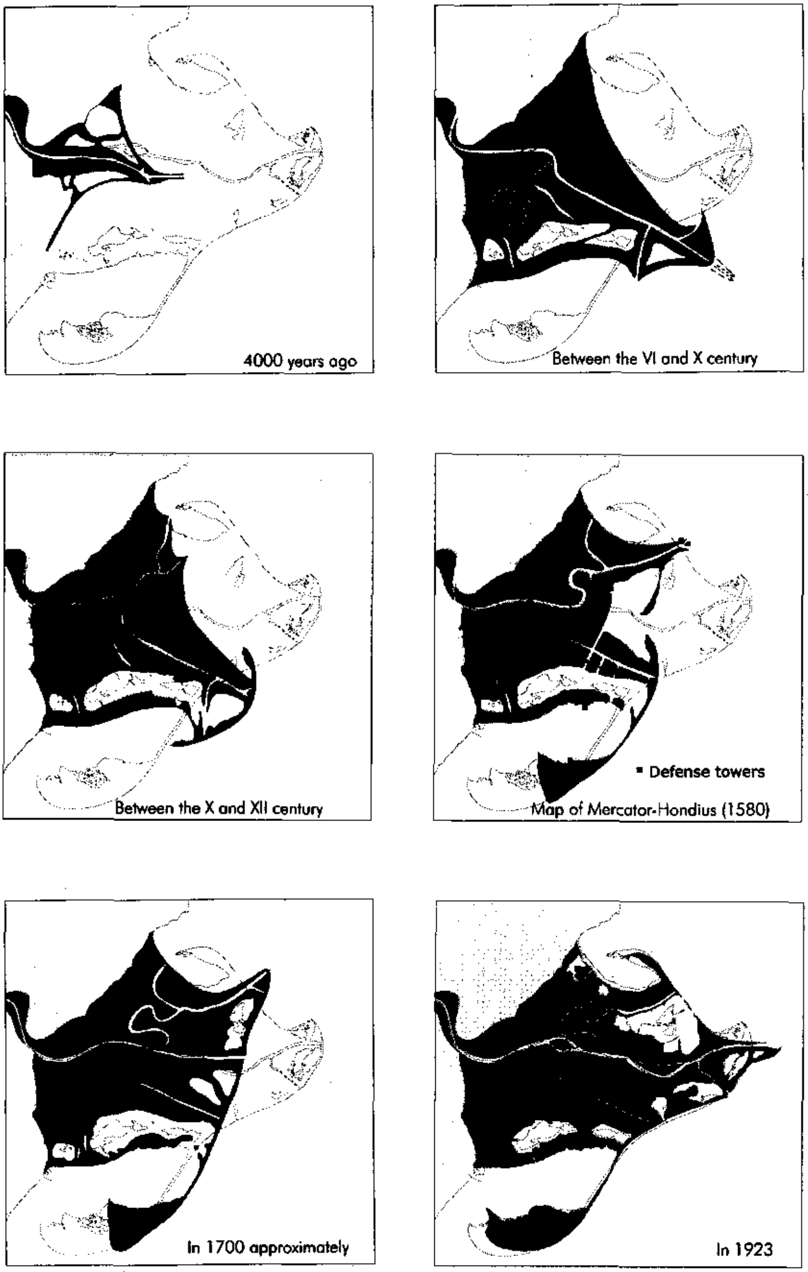

Fig. 2.7. Deltaic evolution of the Ebro Delta during the recent 4.000 years (after Ibàñez et al., 1997).

2.1.7. Modern deltaic environments

The part of the Delta above present sea level, called the deltaic plain, is built up of four major sedimentary environments: fluvial, paludal, fluviomarine and holomarine as shown in Table 2.1 based on Maldonado (1972) and Daniels and Hammer (1986).

Table 2.1. Sedimentary environments and characteristics of the deltaic plain.

Sedimentary Environments		Characteristics
Fluvial	- Tributary fans	The village of Camarles lies on one.
	- Natural Levees	They have an average height of 4 m above sea level at the head of the Delta, declining progressively towards the mouth of the river and interchannel areas.
	- Point Bars	
	- Crevasse (Splay/Delta)	
	- Floodplain/Backswamp	
	- Abandoned river channels	They are of great interest because they have governed deltaic evolution.
Paludal	- Lagoons	Lagoons occupy extensive areas near the shore line and have highly organic sediments. They result from the isolation of a bay by sand bars. Their mean depth is 1 m.
	- Marshes	Marshes are the final evolution stage of lakes or abandoned channels (a marsh spreads across the sediments infilling).
	- Sandy plains	Flat sandy areas with shrub vegetation that are periodically inundated by a thin sheet of water. They are a more advanced stage in the evolution of spits.
	- Channels of current	Small channels that connect and drain the paludal environments. Water drainage is governed by changes in water density, fluvial discharge and sea level fluctuation.
Fluviomarine	- Deltaic Front	It is characterized by sand bars associated with deltaic progradation. These sand bars extend laterally and connect with a sand sheet growing out from the coastline.
Holomarine	- Beaches	Beaches and spits are built up by sand derived from: (1) fluviatile sediments from the mouth of the river carried by long-shore drift; and (2) sediments derived from the erosion of the abandoned lobate deltas.
	- Spits/Sand bars	The spits grow by continuous annexation of shoreface bars to the coastline. Then the sediments carried in by waves develop between the former coastline and the annexed bar.

2.2. THE SOCIO-ECONOMIC BASIS OF THE EBRO DELTA

The present population density in the Ebro Delta is 120 inhabitants km^{-2} (46000 inhabitants). Within the active population, an average of 20% is directly working in agriculture. Fishing (over 20% of the total fish production in Catalonia) and the service sector play also an important role. The industrialization of the Delta is minimal and has developed around the agricultural market such as cooperatives for post-harvest technology and small enterprises for the fixing of agricultural equipment. Tourism is still under expansion.

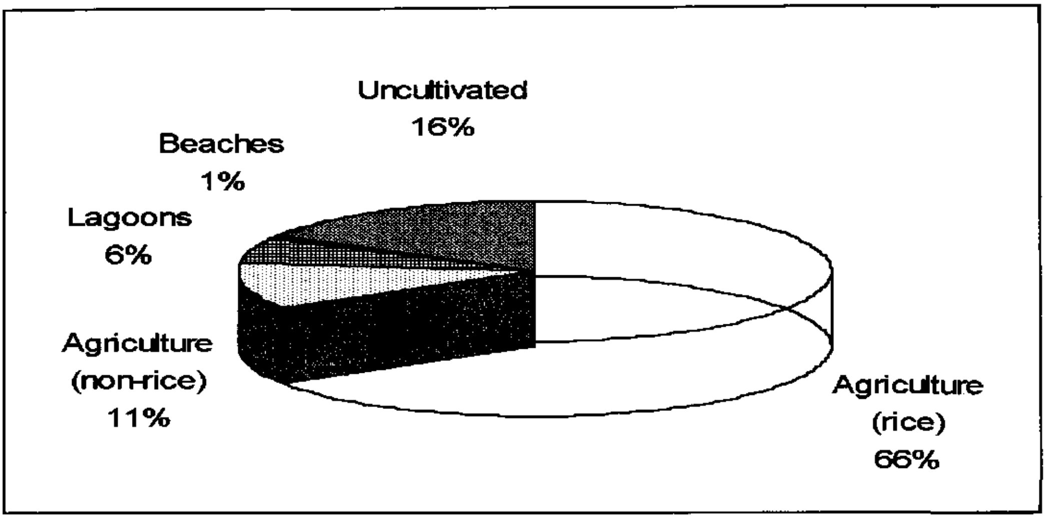

Fig. 2.8. Present distribution of the Ebro Delta surface area (32059 ha) in 1995.

For an idea of the importance of agriculture in the Delta, one needs only to consider the surface area and its distribution according to land-use (Fig. 2.8). The non-rice agriculture refers to non-saline areas where mainly vegetables are grown such as artichokes, cabbage and lettuce mainly for house consumption and close markets.

The agricultural production of the Delta constitutes 12% of the total of Catalonia, and that at an area equivalent to only 1% of the territory of Catalonia. Small farm holdings predominate in the area as shown in Table 2.2.

Table 2.2. Present distribution of farms in the Ebro Delta.

Number of farmers	Size of the farm	Area represented (%)
7243 (93%)	Less than 5 ha	30
436 (6%)	Between 5 and 25 ha	21
98 (1%)	Greater than 25 ha	49

2.3. THE RICE PRODUCTION SYSTEM OF THE EBRO DELTA

A scheme of the rice farming activities in the Ebro Delta is presented in Fig. 2.9.

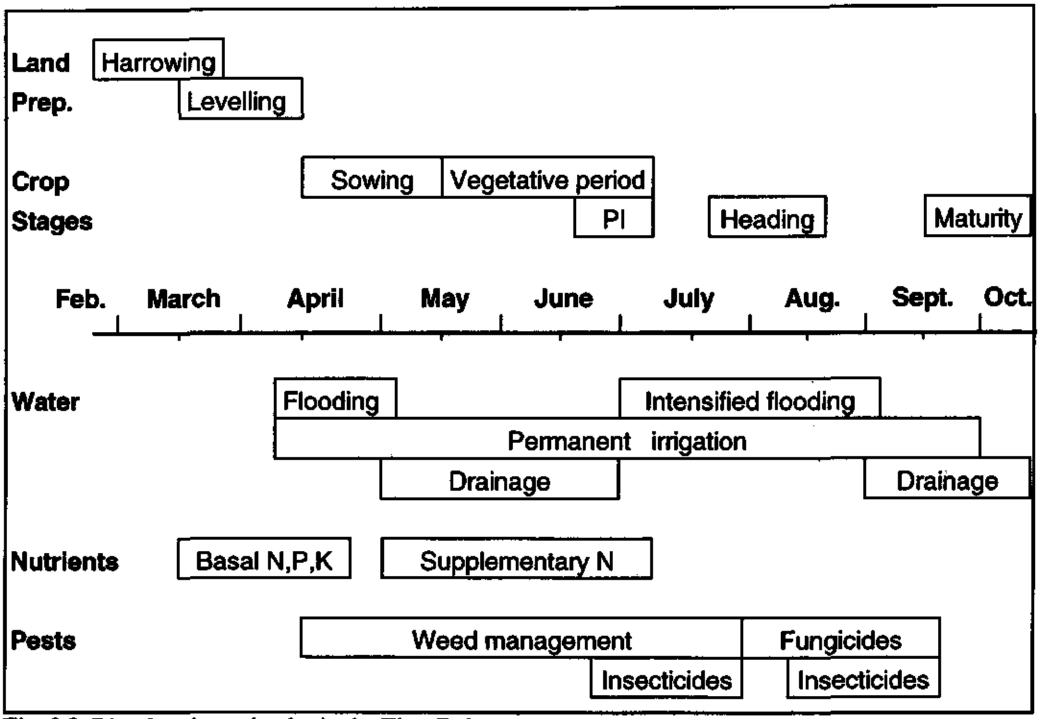

Fig. 2.9. Rice farming calendar in the Ebro Delta.

2.3.1. Land Preparation

Rice farms in the Ebro Delta are divided into rectangular parcels called "sorts" in local jargon (as checks in USA or bays in Australia). The parcels are defined by bunds, of 30 cm height, constructed in relation to topography and perpendicular to the prevailing wind direction (from the north-west). They rarely exceed 3 ha because of the potential wind and wave damage to young rice seedlings in large open water expanses.

After the winter rains, when the soil loses its wetness, rice fields are prepared using different size tractors with varying horsepower. Fields are opened with a chisel plow or disc harrow to allow the soil to dry. One or two diskings to reduce clod size may follow. Later on, smoothing and levelling is necessary each year to remove high and low surfaces created by equipment operations.

To provide a smooth but corrugated surface for anchoring water-seeded rice, large rollers are increasingly being used in recent years. The roller makes grooves in the soil perpendicular to the prevailing wind direction. When rice seed is broadcast into the water, it settles at the bottom of the grooves and is protected from uprooting by wind.

Coarse, cloddy seedbeds are preferred for water-seeded rice: the clods serve as barriers to seedling drift from wind and wave action.
Levelling allows water drainage and maintenance of a uniform water depth that facilitates establishment. High, unflooded areas are notorious for rapid weed growth; low areas collect water and reduce seedling survival. Overly steep slopes make the control of water depth virtually impossible. Levelling to zero grade is mainly done because it provides the most precise control of water depth. On completely flat fields, however, surface drainage for management practices is extremely difficult (Hill et al., 1991).

2.3.2. Crop Stages

Regarding the life cycle of the rice plant, the following stages are distinguished:

• *Sowing*. It takes place from the 15th April to the 15th May. The Ebro Delta is entirely direct-seeded and almost exclusively water-seeded. Pregerminated or dry rice seed is broadcasted into standing water, either by tractor or by aircraft. Rice seed is soaked in water 24-36 h and drained another 24 h. Soaking initiates germination and increases seed weight. The added weight allows the seed to sink to the soil surface. Seeding rates of 500 to 600 grains m^{-2} for short and long-grain cultivars respectively are common (approximately 150 kg ha^{-1}).
In recent years, dry-seeded methods are becoming popular in well drained and non-saline soils. Several variations exist but the most common one is to drill and incorporate the rice seed into dry corrugated soil. Drill seeding requires less seed, has a more uniform emergence but needs more time than broadcast seeding.

The vegetative period goes from germination to the initiation of panicle primordia. The rice needs a minimum temperature of 10°-12°C to germinate. At germination and seedling emergence, the water acts as a thermoregulator to prevent seeds from the low temperatures at night time. The water height over the fields is 10-15 cm. Research and experience indicate that 160-240 plants m^{-2} provide optimum yields. From seedling emergence to panicle initiation, supplementary nitrogen fertilization and weeding practices are regularly performed.

• *Panicle Initiation (PI)*. Panicle initiation is defined as the first appearance of a differentiated apex when examined under a magnifying glass. This occurs around the end of June. By then, an approximate leaf area index of 3 m^2 leaf m^{-2} soil is reached in the parcels and the water is not clearly visible any more.

• *Heading*. Heading is normally defined (Horie et al., 1997) as when 50% of the panicles fully emerge from the flag-leaf sheath and full heading when 80% of panicles are fully emerged. This occurs at the end of July or beginning of August. Leaf area is maximum at that time and in the order of 5 to 7 m^2 leaf m^{-2} soil. In optimal conditions, 400-500 and 600-700 panicles m^{-2} are encountered for short and long-grain cultivars, respectively.
Full heading is close to the date of anthesis or flowering. Anthesis refers to a series of events between the opening and closing of the spikelet, lasting about 1-2.5 hours. Rice is a self pollinating plant. Especially the 12-16 days before anthesis, rice is very sensitive to cold temperature (Angus et al., 1993). Temperatures below 18°C often inhibit the development of the spikelet and the flowers remain sterile.

• *Maturity*. The ripening period is characterized by grain growth, changes in grain colour, loss of grain moisture and senescence of leaves. Optimal temperatures for ripening are 20° to 22°C. Agronomically, maturity is defined as the time when the maximum grain weight is reached. It is usually several days before harvesting. The time of harvest is usually determined by grain colour and leaf senescence. To avoid grain fissuring and damage in the combine, the crop is harvested at 19-23% grain moisture. The grain is delivered to the co-operatives, where it is carefully dried to maintain milling quality. The harvesting period in the Ebro Delta ranges from the 10^{th} September to the 10^{th} October.

In the Ebro Delta, at present, mainly short or round-grain cultivars (basically Tebre, Bahia, and Senia) are grown. Maximum productions of 11,000 kg ha^{-1} (at 14% moisture) are achieved with an average of 6,500 kg ha^{-1} (Caballero i Lluch, 1992). Recent developments in world rice markets have introduced long-grain cultivars such as Lemont and Thaibonnet or L-202. The L-202 developed in California (USA) has given better results than Lemont developed in Texas (USA) because of more similar wea ·r conditions.

2.3.3. Water Management

Rice is permanently flooded for most of the growing season, although short drainage periods may be needed to correct specific crop disorders dependent on herbicides application, root fixation, etc. Water use varies with weather, soil type and management practices. Field levelling is the most important factor in efficient irrigation management. About 1200 mm of water is needed for evapotranspiration, but the amount of irrigation water delivered is about 2600 mm (average discharge of 2 l s^{-1} ha^{-1}).

Water management practices start with a flooding. The fields are flooded from 10^{th} to 25^{th} of April. After germination, the water level is lowered to 5 cm and is gradually increased as the crop develops further on. An excessive amount of water consumption during vegetative stage has negative effects on the plant, elongating too much the stem and reducing the rooting depth. During reproductive growth, irrigation depth is commonly 20-30 cm to protect developing panicles from high or low temperatures. In preparation for harvest, some farmers prefer to dry the field while others keep the water on.

An irrigation is practised generally in the Ebro Delta from October to January if the land lies fallow for a short time. The main purpose of the irrigation is to flush out the surface salts as far as possible.

2.3.4. Nutrients

The soil is mainly fertilized during the land preparation period. The requirements vary with soil type, cropping history and cultivars. Nitrogen is the nutrient most commonly added in rice production. In general 120-180 kg ha^{-1} of N in a reduced form (urea, ammonia, ammonium sulphate) is applied; in one dose, or split application at tillering and/or at panicle initiation. Phosphorous and potassium doses are on average 100 kg K ha^{-1} and 50 kg P ha^{-1} as basal application.

2.3.5. Pest Management

A wide range of weeds, diseases and insects (stem borers such as *Chilo suppressalis*) infest rice in the Ebro Delta. Weeds are a major problem, because they have a more competitive advantage in direct seeded than in transplanted rice. Annual grasses (*Echinocloa spp.*), broadleaves (*Potamogeton spp.*) and sedges (*Cyperus spp.*) commonly infest rice. To minimize the impact of weeds on yield, herbicides (such as Molinate and Bentazona) combined with cultural practices are used. Puddling before sowing and weeding by hand (until the rice plant has become so tall that cannot be weeded without damage) are nowadays performed, especially for the so-called wild rice, red rice or "crodo" as it is called in Italy.

Blast caused by *Pyricularia oryzae*, brown spots by *Helminthosporium oryzae*, and stem rot by *Fusarium spp.* or *Sclerotium oryzae* are encountered. Two to three applications of fungicides (mainly Carbendazima and Mancozeb) in August are common, especially when high temperatures go along with high relative humidity.

Soil distribution on the left bank of the Ebro Delta

Abstract:
The spatial distribution of soil and its attributes on the northern part of the Ebro Delta (left bank), Catalonia (Spain), were studied. The soils were classified based on (i) soil development, (ii) textures, (iii) drainage status and (iv) soil salinity. Where soils had not developed yet, its characteristics reflected parent material variability. The textures of the sediments were related to the depositional environments and landforms. Drainage status was quantified and soil salinity measured, while their causes and distribution were analysed. The survey methodology, in such a deltaic area with flat landscape and high textural and taxonomic variability, was innovative as it combined expert knowledge, grid survey and short-distance measurements. A Soil Geographical Database (SGD) or geo-information system was developed to store, analyse and present soil data. Especially the flexibility of the database management system, the facility to interact with the land information user and the possibility of combining with other digital information was of great value. Two methodologies were used to define the required terrain features:

(i) The "object-oriented" approach which assumes that terrain features can be defined with each having a geometric position and shape. Datasets with discrete units concerning soil type, textural-size class and epipedon texture (USDA) were created by means of this method. Limits were drawn based on the refinement's of the surveyor model.

(ii) The "field" approach which assumes terrain features to be spatio continuum. Continuous datasets of elevation and various soil properties, relevant in the study area, were created by interpolation from soil data.

Differences within geomorphological units, and their specific effects on soil types, were better expressed with the object-oriented approach using the complementary help of ortophotomaps. Differences within a unit, of elevation and simple soil properties (such as salinity and drainage status) that change gradually, were better expressed in the "field" approach. The design of schemes a priori, that combine both approaches for collecting, analysing and presenting the data is of great value for land-use systems analysis.

Keywords: Soil database; Salinity; Drainage; Discrete dataset; Continuous dataset.

Based on a paper submitted to "Arid Soil Research and Rehabilitation": Casanova, D., Boixadera, J., Llop, J.. Development and applications of a soil geographic database in a deltaic environment under rice cultivation.

3.1. INTRODUCTION

Soil properties play an important role in activities such as agriculture, land-use planning, building, erosion control, environmental protection and nature conservation (Van Lanen, 1991). All these activities require different information about attributes of the soil and soil-forming processes (Bregt, 1992). The soil surveyor describes the spatial distribution of soils based on field observations, sample measurements and geomorphology. The resulting survey data is traditionally presented in the form of a soil map and report. Soil data, as it was traditionally treated, is insufficient to predict parameters needed by agro-meteorological and environmental models (King et al., 1994; Magaldi, 1995; Bouma, 1989). Furthermore, countries have developed different methods for soil survey at various scales and objectives. Therefore, the creation of a Soil Geographical Database (SGD) or Soil Geo-Information System is widely supported nowadays.

Until now, no soil map or study had been made which focused on the soils of the Ebro Delta (Catalonia, Spain) except for a study in the 1960's in which some properties of the soil and the irrigation water were taken into account (Proyecto de saneamiento y riegos del Delta del Ebro, 1966). The "Departament d'Agricultura Ramaderia i Pesca (DARP)" undertook a research project of rice cultivation, the main land-use in the study area, that did not consider soil properties variability (Caballero i Lluch, 1992). Other studies made of the Ebro Delta (Maldonado, 1972; Jiménez and Sánchez Arcilla, 1993; Ibàñez et al., 1995) are either geological or biological, and focus on the evolution, sedimentology, flora and fauna rather than on agro-ecological aspects.

This chapter covers the development of a Soil Geographical Database (SGD) on the northern part of the Ebro Delta (left bank). It presents the SGD as a tool that enables to store, manipulate and present data on the environmental variables of the study area in a flexible way.

As part of this study, special emphasis was given to assessing drainage status and soil salinity; the poor drainage conditions and high salinity of some of the soils in the study area was expected to have a major influence on land-use.

The traditional approach used to perform a soil survey is shown in Fig. 3.1(a). Obviously, in a deltaic area is almost impossible to delineate landscape units based merely on photointerpretation. Additionally, a digitized map contains no more information than the initial paper map. Consequently, we have inverted the traditional methodology for collecting and managing the data. Figure 3.1(b) illustrates the procedure chosen in this research project.

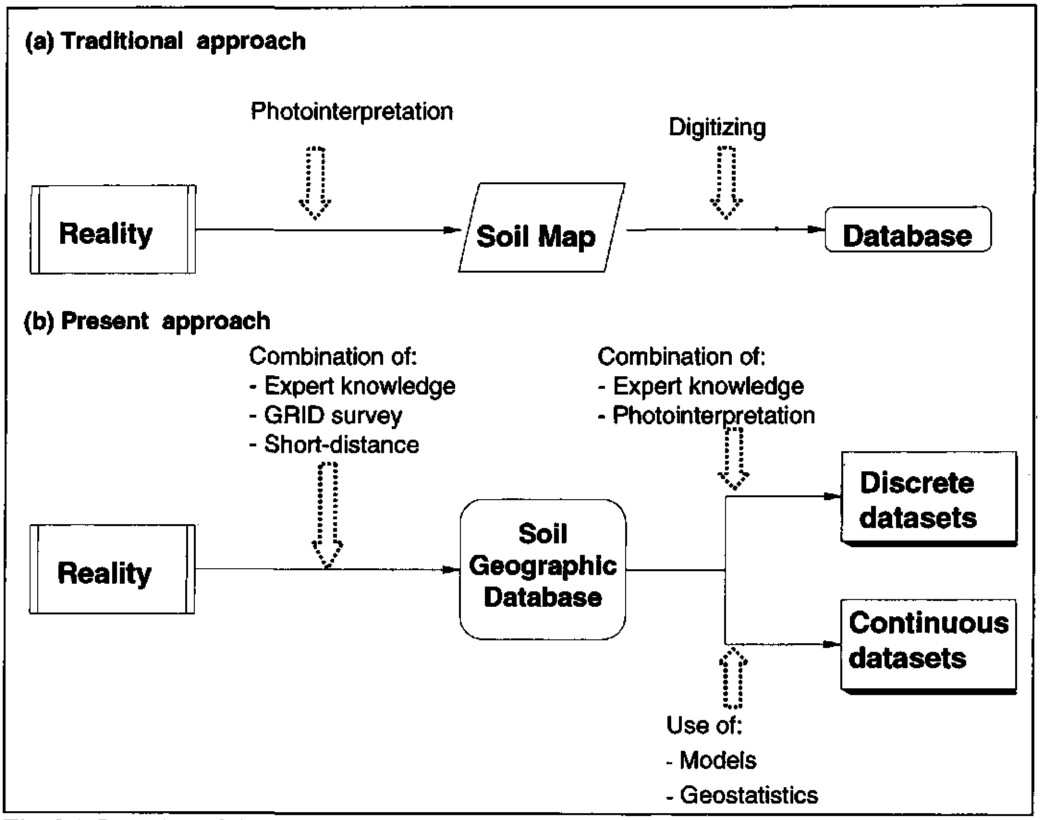

Fig. 3.1. Inversion of the process in the production of soil data information on the left bank of the Ebro Delta. Solid lines are flows of material, dotted lines are flows of information (modified from King and Le Bas, 1996).

Section 3.3 shows the two different approaches (Molenaar and Richardson, 1994) for analysing and presenting the data:

(i) The "object-oriented approach (Section 3.3.1)" describes the terrain using discrete units. A scheme for classifying the soils is given based on an understanding of the main soil properties and processes. Limits were drawn based on the refinement of the surveyor model by combining the soil data over the ortophotomaps. Soil type, particle-size class and epipedon texture datasets are produced.

(ii) The "field-approach (Section 3.3.2)" describes the earth as a continuum for specific properties. Continuous datasets of elevation and various soil properties, relevant in the study area, are generated by linear interpolation from point data and its attributes, considering the entire study area as one unit.

Thereafter, a discussion (Section 3.4) on the soil units, genesis, relation to geomorphology, soil properties and land-use is presented. This chapter concludes (Section 3.5) with a discussion on the potential uses of the soil database and the two approaches of analysing and presenting the soil data.

The annexes contain field observed and measured properties (Annex 3.1), laboratory (physical and chemical) measured properties (Annex 3.2), and chemical properties of the groundwater (Annex 3.3) for each of the main soil types.

This research is part of two large projects; one of the DARP (Autonomous Government, Generalitat de Catalunya) aiming to map the entire Ebro Delta and another of the Wageningen Agricultural University (WAU, The Netherlands) attempting to quantify the effects of land conditions on rice growth for a case study in the Ebro Delta. This part was conducted as a collaboration between the "Department of Soil Science and Geology (WAU)" and the "Section of Resources Evaluation and New Technologies" of the DARP.

3.2. MATERIALS AND METHODS

3.2.1. Data collection

Fieldwork was conducted during the winters of 1994-1996. According to Bouma et al. (1993), an efficient sampling scheme should base the number of observations on spatial heterogeneity and not only on the scale of the map to be made. In this survey, based on expert knowledge acquired from mapping other similar environments, an average of 1 observation per 20 hectares was selected.

3.2.1.1. Desk studies and map compilation

The selected study area, left bank of the Ebro Delta, has in total 11922 ha, of which 10224 ha are cultivated land. The field maps chosen were orthophotomaps at 1:25000 scale (ICC, 1992; sheets C522-II,III,IV and C523-III). Data on the geology was provided by the geological maps 1:50000 (IGME, 1979; sheets number 522 and 523). Maps at scale 1:10000 of the study area from 1966 with elevation points were provided by the "Irrigation Community of the Ebro Delta". These maps had been used for designing the irrigation system, infrastructure, etc., and their quality was supported by their use in many different governmental departments.

3.2.1.2. Field methods

The soil survey was conducted in three steps:

(i) In the various physiographic units derived from the geological map, 80 soil pits were dug during the winter of 1994. Full profile descriptions were performed based on the SINEDARES methodology (CBDSA, 1983) and groundwater samples were taken. In addition to the morphological description of the soil horizons (described below), chemical analyses of the sampled horizons were performed.

(ii) A grid survey (500×500 m) was performed during the winters of 1995 and 1996. Augerings at grid intersection (a total of 410 auger-holes) were completed each to a depth of at least 150 cm. A morphological description of the different horizons and layers was undertaken including: Colour, texture, mottling, oxidation/reduction conditions, and a classification of the soil at phases of family level (SSS, 1992).

(iii) Additional closely-spaced augering were incorporated into the sampling scheme (10% of the total data set, approximately 50 observations) to allow for geostatistical treatment of the data.

Four major methods are available for salinity surveys of irrigated land:

(i) visual field observations that relate natural vegetation and soil surface characteristics to the soil salinity,

(ii) collection of soil samples in the field and measurement of the conductivity of the soil extract, $EC_{1:5}$ (of the extract in a weight ratio of 1:5) and EC_e (of the extract of the saturated paste), in the laboratory,

(iii) electrode sensors, and

(iv) electromagnetic induction (EM) sensors. The EM-sensor has become the first choice for salinity surveys in different parts of the world; starting in the United States (Corwin and Rhoades, 1982; Lesch et al., 1992) and including Canada (Wollenhaupt et al., 1986), Australia (Cook and Walker, 1992; Slavich, 1990), Spain (Díaz and Herrero, 1992), Senegal (Ceuppens et al., 1997).

In this research, (ii) and (iv) have been used for quantification. The EM sensor measurements followed by laboratory analysis were used. At every auger hole, an electromagnetic measurement was taken. For one in every five measurements, samples were taken for further analysis of $EC_{1:5}$ in the laboratory (Richards, 1954), at depths of 0-30 cm, 30-60 cm, 60-90 cm and 90-120 cm.

Calibration of the electromagnetic sensor (EM-38).

Until now, various models have been used to determine soil salinity from electromagnetic induction (EM) measurements (Lesch et al, 1992; Díaz and Herrero, 1992; Wollenhaupt et al., 1986). In this study, the purpose was to estimate soil salinity averaged over the soil profile (from 0 to 120 cm). For it, the four values obtained at every observation point were averaged $(EC_{1:5})_{av}$. $(EC_{1:5})_{av}$ was used for calibrating the electromagnetic sensor. EM values were normally distributed and no log-transformed was found necessary. Figure 3.2 shows the values of $(EC_{1:5})_{av}$ against the relative response of the EM sensor in the horizontal position (EMH). The statistical analysis showed that the electrical conductivity was proportional to EMH. Including an intercept, as well as the relative response of the EM sensor in the vertical position (EMV), did not significantly improve the accuracy of the estimate. EMV values were so highly correlated with EMH that they did not give additional information. This results are in accordance with other authors such as López-Bruna and Herrero (1996) and Hendrickx et al. (1992). In the equation:

$$(EC_{1:5})_{av} = B_0 \times EMH \qquad \text{(Eq.3.1)}$$

$(EC_{1:5})_{av}$ and EMH are given in dS m^{-1} and B_0 is an empirical regression coefficient. This equation as shown in Fig. 3.2 was used in this study for predicting electrical conductivity. Differences in field moisture content cause part of the none explained variance in the correlation.

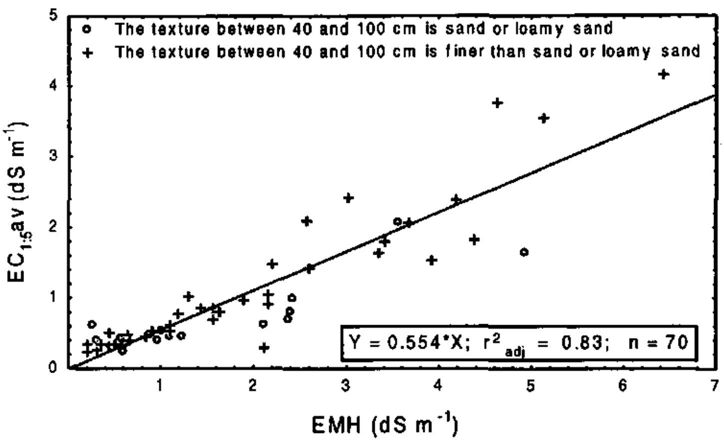

Fig. 3.2. Relationship between electrical conductivity of the extract 1:5 averaged from 0 to 120 cm $(EC_{1:5})_{av}$ and electromagnetic induction readings taken with the coil horizontal to the soil surface (EMH). The slope has a standard error of 0.02 and a p-level < 0.001.

Electrical conductivity values are commonly given in literature as EC_e. EC_e is a more reliable indicator for soil salinity than $EC_{1:5}$ because the dilution is lower and the moisture content of the sample is closer to the moisture content in reality (Richards, 1954). The saturated paste method, however, is more laborious than the $EC_{1:5}$. The results of various selected soil horizons where electrical conductivity of the extract in the saturated paste and in a 1:5 dilution were measured had a linear relationship, independent of textural class:

$$EC_e = -1.62 + 7.75 \times EC_{1:5}, \quad (r^2_{adj} = 0.92, n=55) \qquad \text{(Eq. 3.2)}$$

3.2.1.3. Laboratory methods

Analyses were performed in the "Laboratori Agroalimentari; DARP, Cabrils". The methods performed in the analyses of soil samples were the recommended by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 1986):

- Granulometry. It was determined by using the corresponding sieves and pipette; clay, silt, fine sand ($0.05<D<0.5$ mm) and coarse sand ($0.5<D<2$ mm).
- pH. It was determined potentiometrically by a pH-meter from the soil water extract 1:2.5 and from the saturated paste.
- Electrical conductivity. Measured from the extract of the saturated paste (EC_e) and from the extract of a soil dilution with water in a weight ratio of 1:5 ($EC_{1:5}$), Richards (1954).
- Calcium carbonate equivalent. Determined by the Bernard calcimeter.
- Organic matter content. Using the Walkey - Black method.
- Cation exchange capacity and exchangeable potassium. Extraction with ammonium acetate 1N at pH=7.
- Available phosphorous. Using the Olsen - Watanabe method.
- Total N using the Kjeldahl method.
- Cations of the saturated extract; Sodium and potassium by photometry, calcium and magnesium by absorption.
- Anions of the saturated extract. Chlorides, sulphates bicarbonates and nitrates by chromatography.

In the groundwater samples; pH, electrical conductivity, sodium, calcium, magnesium, potassium, chloride, sulphate nitrate, carbonate and bicarbonate were analysed. These results are in Annex 3.3.

3.2.2. Data storage

The collected data was stored in a digital form in order to record the major components of geographic data that is: (i) geographic position, (ii) attributes or properties, and (iii) time; in other words, where the object or feature is, what it is, and when did it exist. Elements within geographical space were referenced. Attributes were categorized as:

- Nominal: data that can be placed into classes, determination of equality (soil type).
- Ordinal: data that can be ranked, determination of greater or smaller (drainage class).
- Interval: determination of equality of intervals or differences (clay/silt/sand percent).
- Ratio: measurements that have a true zero, determination of equality of ratio (elevation, soil salinity).

The data was digitized using the geographic information system ARC-INFO at the DARP. The present database model (see Table 3.1), once digitized and stored, comprises five main structural components as shown below. They are independent one of another, but they can be combined by the geometry. The first three are basic data and the last two are processed data.

- Geology. Sedimentary environments derived from the Spanish geological map (IGME, 1979; scale 1:50000) were digitized as objects.
- Field survey observations. Complete profile, site description and analytical data were recorded as attributes and the locations were digitized as points.
- Digital elevation model. Over 4000 points were digitized from the topographic maps (scale 1:10000) creating a very detailed elevation database of the study area.
- Discrete datasets. The generated datasets of soil attributes, based on classical classification as mentioned in Section 3.3.1, were digitized as objects.
- Continuous datasets of elevation and various soil properties, derived as discussed in Section 3.3.2, were stored as grids.

Table 3.1. Scheme of the soil geographical database for the Ebro Delta left bank.

Basic module	Information layer	Data incorporated	Type of attributes
- Geological map of Spain.	Coverage of polygons.	IGME (1979) digitized maps 522 and 523.	- Sedimentary environments.
- Field survey observations.	Coverage of points.	File with field point data gathered from auger holes and soil pits: position, attributes and time.	- Morphological features. - Physical measurements. - Chemical measurements. - Soil classification.
- Digital elevation model.	Coverage of points.	File with position and elevation.	- X,Y,Z co-ordinates.
- Discrete datasets.	Coverage of polygons.	Classification based on classical methods.	- Soil mapping units (SSS, 1992).
- Continuous datasets.	Grid of cells	Interpolation of digital data.	- Elevation and various soil properties.

3.2.3. Data analysis

The stored data was analysed to derive the desired information. The term analysis is used in this context, in a broad sense. It includes both simple selection of data as well as the transformation of data for spatial analysis. The chosen database management system was INFO within ARC-INFO.

All the field observations (soil pits, regular grid survey and short-distance measurements), and laboratory measurements were used in the analysis. Two approaches (Molenaar and Richardson, 1994) were taken:

(i) The "object-oriented" approach which gave datasets with discrete units. This approach describes the area in objects or discrete units which have specific geometry and thematic properties.
(ii) The "field" approach which gave continuous datasets. This approach describes the terrain as a continuum for specific thematic properties. The specific aim was to convert point data with its attributes into continuous datasets.

In approach (i), limits were drawn based on the refinement of the surveyor model. Datasets were produced by combining the field point with a given nominal attribute over the ortophotomaps.

In approach (ii), nominal data may not be treated. Therefore, epipedon textural class (USDA) and particle-size class were transformed using the middle values of sand, silt and clay for every class as shown in Tables 3.2 and 3.3, respectively. To calculate the composition percentages at 40-60 cm and 80-100 cm, homogeneous particle-size classes were given the same values. The particle-size classes with abrupt changes were separated selecting the corresponding value at 40-60 cm and the other value at 80-100 cm.
The other soil properties of which continuous datasets are presented were ordinal, interval or ratio type of data. Elevation was considered because of its key role in relation to soil properties in such deltaic areas. The electromagnetic values, in the horizontal position (EMH), were converted to soil salinity $(EC_{1:5})_{av}$ values according Eq. 3.1 (see Fig. 3.2). EC_e values were derived from $(EC_{1:5})_{av}$ according Eq. 3.2. The system to quantify soil drainage status is presented in Fig. 3.3.

Table 3.2. Surface (Ap) textural (USDA) classes of the soils on the study area with its identifiers assigned in the discrete datasets and clay, silt and sand percentage values assigned in the continuous datasets.

	Identifier	[Clay]	[Silt]	[Sand]
Sandy	0	5	5	90
Loamy sand	1	5	15	80
Sandy loam	2	10	25	65
Fine sandy loam	3	10	30	60
Loam	4	18	40	42
Silty loam	5	14	65	21
Sandy clay loam	6	28	14	58
Clay loam	7	34	34	32
Silty clay loam	8	34	56	10
Silty clay	9	46	46	8

Table 3.3. Particle-size classes (from the base of the slowly permeable layer, approx. 35 cm, to 100 cm depth) of the soils on the study area (SSS, 1992) with its identifiers assigned in the discrete datasets and clay, silt and sand percentage values assigned in the continuous datasets.

	Identifier	[Clay]	[Silt]	[Sand]
Sandy	0	5	10	85
Fine	1	40	30	30
Fine silty	2	26.5	66	7.5
Coarse silty	3	9	84	7
Fine loamy	4	26.5	16	57.5
Coarse loamy	5	9	33.5	57.5

When predicting, the spatial dependence is to be taken into account because the observations close to a prediction location are likely to be more similar to the unobserved value than observation at a larger distance (Stein, 1991). The soil attributes were treated independently from one another. The chosen program was the TOPOGRID component of Arc-Info (GRID module) which is an interpolation method based upon the ANUDEM program (Hutchinson, 1989). This procedure embodies an interpolation accompanied by a drainage enforcement algorithm which takes into account direction and permits to detect errors. All the datasets had been interpolated for the entire study area as a unit with a cell size of 25×25 m.

3.2.4. Data presentation

The main result of this study is the soil geographical database (SGD) in itself. Various applications of it, however, are presented:

- Discrete datasets overlaying a satellite (SPOT) image of (i) soil type, and (ii) epipedon texture (USDA) and (iii) particle-size class, from the base of the slowly permeable layer, approx. 35 cm, to 100 cm.
- Continuous datasets of elevation and various soil properties considered to be most important for land-use such as: soil salinity, drainage status, epipedon clay and sand content, and clay content at 40-60 cm and 80-100 cm from the soil surface.

3.3. USE OF THE "SGD" TO PRESENT SOIL DATA

3.3.1. Discrete datasets and their thematics

Soil mapping units in deltaic areas have high textural and taxonomic variability (Pons and Zonneveld, 1965). Soil variability can range from minor to extreme depending upon the complexity of depositional environments present (Daniels and Hammer, 1986).

Table 3.4. Scheme of the main soil types on the left bank of the Ebro Delta.

Profile development[1]	Texture[2]	Drainage status[3]	Soil types
Non or very slight developed (N)	Coarse (C)	1	
		2	
		3	NC3
		4	
		5	NC5
		6	
		7	NC7
		8	
		9	NC9
	Medium to fine (M)	1	NM1
		2	NM2
		3	NM3
		4	NM4
		5	NM5
		6	NM6
		7	NM7
		8	NM8
		9	NM9
Developed (D)	Coarse (C)	1	
		2	
		3	
		4	
		5	
		6	
		7	
		8	
		9	
	Medium to fine (M)	1	
		2	
		3	DM3
		4	DM4
		5	DM5
		6	
		7	DM7
		8	
		9	
	Medium over peat (P)	9	DP9

[1] Profile development is considered to occur if a histic horizon or calcium carbonate accumulation (a petrocalcic horizon, a hypercalcic horizon, or calcium carbonate nodules) are present within 100 cm depth from the mineral soil surface.

[2] Coarse texture indicates a texture of loamy fine sand or coarser. This parameter refers to the texture of all the materials from the base of the Ap horizon to 100 cm.

[3] A detailed classification of the soil drainage status is presented in Fig. 3.3. They can be grouped, however, as; "From 1 to 5" when reduction conditions start below 50 cm from the soil surface and excluding the ones due to rice cultivation. "From 6 to 9" when reduction conditions appear between the soil surface and 50 cm depth.

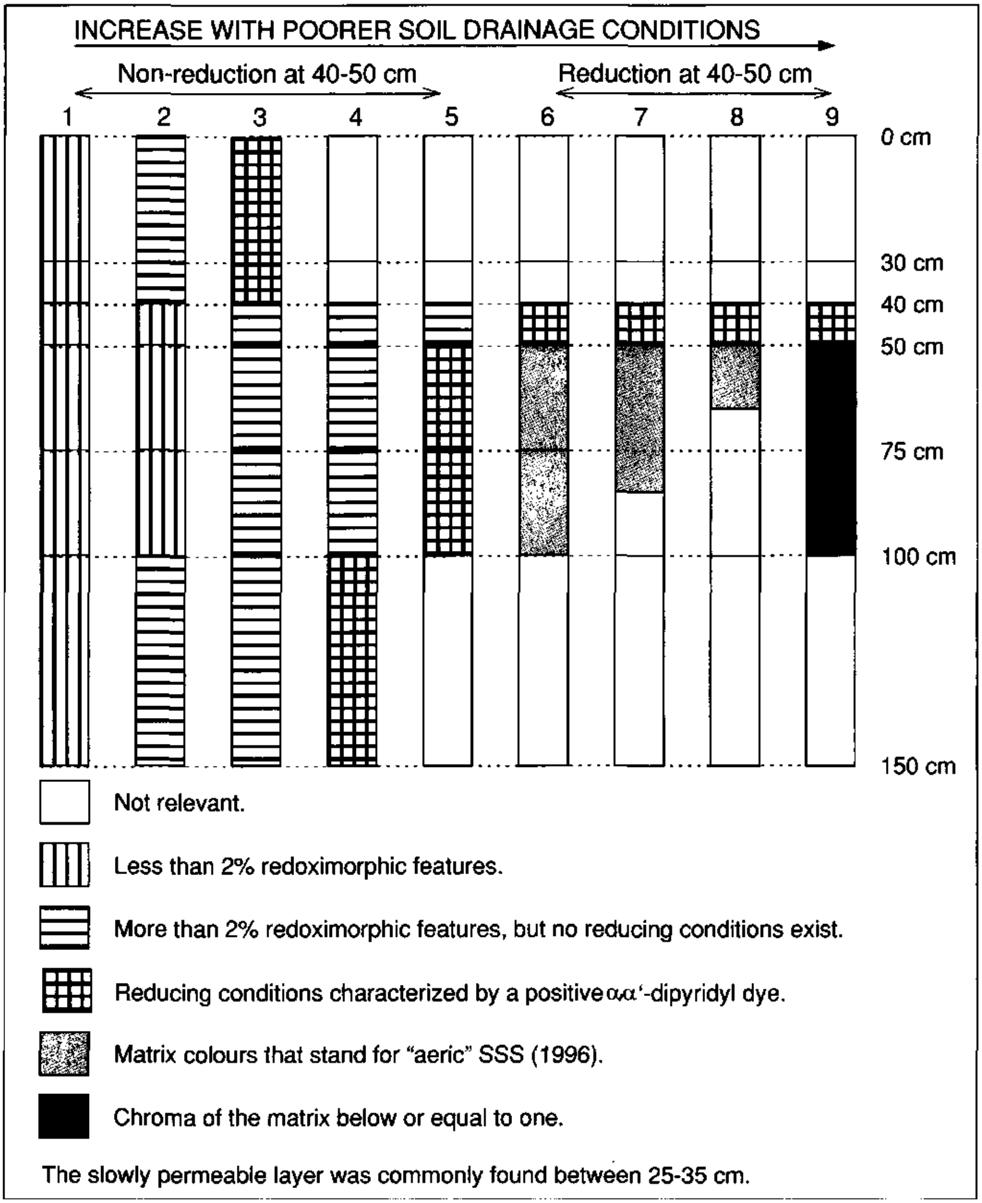

Fig. 3.3. Scheme for quantifying soil drainage status (surveyed on bare soils after the winter rains).

The discrete soil datasets follow the concepts and terminology of Soil Survey Manual (USDA, 1993). Mapping units were made traditionally joining together several concepts. We used: (i) soil type (Table 3.4 and Fig. 3.3), (ii) particle-size class (Table 3.3), (iii) topsoil texture (Table 3.2) and (iv) soil salinity. In the present study, each of these items was kept as a separate layer in the soil geographic database in order to make the analysis easier.

The soil types of the study area were grouped into the general scheme illustrated in Table 3.4 based on profile development, coarse texture (from the base of the Ap to 100 cm depth) and drainage status. A system to quantify soil drainage status, combination of experience gained working in similar environments and SSS (1992), was developed for the specific characteristics of this study area based on soil morphology and field measurements as shown in Fig. 3.3. It ranged from 0 to 9, the increase corresponding with a poorer soil drainage conditions.

Soil types can be further subdivided. Based on SSS (1992), the structure for soil classification is described below. The soil moisture regime in the study area is xeric; many soils, though, had aquic conditions. The taxonomic unit used was the family.

• *Soil subgroup level.* The various soil types of the study area can be grouped as shown in Table 3.5 at subgroup level.

Table 3.5. Soil classification (SSS, 1992) at subgroup level in relation to the soil types.

Soil type	Soil Subgroup	Soil type	Soil Subgroup
NM1,2,3,4	Oxyaquic xerofluvent	DM3	Petrocalcic xerochrept
NM5	Aquic xerofluvent	DM4	Aquic xerochrept
NM6,7	Aeric fluvaquent	DM5	Calcixerollic xerochrept
NM8,9	Typic fluvaquent	DM7	Typic epiaquept
NC3	Oxyaquic xeropsamment	DP9	Thapto-Histic fluvaquent
NC5	Aquic xeropsamment		
NC7,9	Typic psammaquent		

• *Soil family level* is defined based in the following soil characteristics:

- Soil temperature class; Thermic for all soils
- Calcareous class; Calcareous for all soils
- Mineralogy class; Mixed; NC3, NC5, NC7, NC9, NM1-8
  Carbonatic; NM9,DM3,DM4, DM5, DM7, DP9.
- Particle-size class; It refers to the depth from the base of the epipedon to 100 cm. Classes were extremely variable in the study area as usual in such deltaic environments. They were not always homogeneous down the profile and abrupt changes were identified. They were grouped finally in 15 particle size classes with 6 homogeneous (as shown in Table 3.3) and 9 heterogeneous (combinations of those 6). The distribution of particle-size classes within soil types is shown in Table 3.6.

Table 3.6. Soil types and particle-size classes (Table 3.3, e.g. 0= sandy and 1/0 = fine over sandy) distribution in hectares on the study area.

	0	1	2	3	4	5	1/4	1/5	1/0	2/1	2/5	3/0	5/2	0/1	0/5	Total
NM1						170.1										170
NM2		107.7	141.4	80.0	46.9	325.4	9.9				79.9		31.2		33.2	856
NM3		178.0	74.2				13.8	0.8		71.5	143.6		120.6			602
NM4		508.0	202.9	218.6	6.5	60.8	165.5	38.1	16.9	87.9	121.1		27.9	52.2	5.1	1511
NM5		569.7	42.3	14.0	79.5	147.8	149.5	49.5	91.3	7.3	75.1		64.4	33.7		1324
NM6		95.5	84.5		36.7	17.7	16.6	27.1			66.6		45.2	41.6	15.5	447
NM7		149.1				18.8	95.5	46.2	240.1	20.9	26.1				68.4	665
NM8		325.7	210.2			32.7	84.4	7.5	212.8		8.2	13.9	18.7	17.5	53.7	985
NM9		295.3	202.3	21.4	69.4	10.5	65.9		104.6		2.2	74.1	7.5			853
DP9		4.5	112.1													117
NC3	289.2															289
NC5	403.5															403
NC7	1085															1085
NC9	414.4															414
DM3		19.2			221.7	69.3				7.2						317
DM4		62.1	24.9													87
DM5					25.5											25
DM7		24.9	46.1													71
Total	2192	2340	1141	334	486	853	601	169	666	195	523	88	315	145	176	10224

• *Phases of mapping units* consider differences in soil which have not been recognized as different until now in the scheme, but which are relevant to potential uses of certain soils. Two soil properties have been considered at this level:

- Texture of the epipedon; The fine-earth fraction was used for determining texture (USDA) of the epipedon. The identified topsoil textural classes were shown in Table 3.2. The distribution of Ap textural classes within soil types is shown in Table 3.7.
- Soil salinity (dS m^{-1}); It is treated in the next section.

Table 3.7. Soil types and surface (Ap) textural class (shown in Table 3.2), distribution in hectares on the study area.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**Total**
NM1				115.7	54.6						170
NM2				56.9	578.8	141.8			128.1		906
NM3					149.3	351.2			107.9		608
NM4				19.6	237.2	727.4			442.1	0.9	1427
NM5		5.8	51.3	40.2	258.8	326.8	247.0	2.3	443.4		1376
NM6					155.8	103.1			182.9		442
NM7		68.0	1.1		147.9	89.0	4.6	73.5	301.6		686
NM8		100.2	69.3		252.2	215.3		25.8	316.5		979
NM9				1.5	127.9	322.9			368.8	12.5	834
DP9					4.3	65.0			45.9		115
NC3			32.8		96.5	105.2			48.7		283
NC5	15.8	90.9	230.3		7.4	14.6		20.1	24.3		403
NC7	13.9	184.5	497.7		110.8	100.3	65.6	65.3	48.7		1087
NC9	25.5	70.4	226.4		55.6	0.1	29.5		0.3		408
DM3					194.5	32.8			89.9		317
DM4									87.4		87
DM5						0.5			25.0		25
DM7					10.9	20.3			40.0		71
Total	55	520	1109	234	2442	2616	347	187	2701	13	10224

The discrete soil datasets are presented as:

- Soil-type; (Plate 3.1).
- Particle-size class from the base of the slowly permeable layer, approx. 35 cm, to 100 cm; (Plate 3.2).
- Topsoil texture; (Plate 3.2).

3.3.2 Continuous datasets and their thematics

The data stored in the soil geographical database was manipulated within the geographic information system, ARC-INFO. Based on the methodology described in

Section 3.2.3, continuous datasets were generated which allow to visualize the spatial distribution of any variable derived from point observation. This approach is used for elevation and various soil properties considered to be most important for land-use.

3.3.2.1. Elevation

The topographic dataset of the study area presented as Plate 3.3 helps to understand the landforms, soils and their distribution within the study area. It shows that elevation is closely related to depositional environment. In the fluvial environments, the low-elevation areas tend to be more poorly drained and to have finer material than the high-elevation areas. A gradual decrease in elevation exists from the river banks to the sea shore and within the river banks as they come closer the river mouth. Coastal environments are low in elevation.

3.3.2.2. Soil Salinity

The land information user should be aware of the intra-annual variability in soil salinity. The obtained soil salinity dataset is presented in Plate 3.4. Figure 3.4 shows the soil salinity variability among soil types from observation points. It illustrates how soils DM3, DM4, DM5, DM7 and DP9, well-developed and high in elevation, are clearly non-saline. The non-developed but well-drained soils, NM1 and NM2 are also non-saline. The rest of soil types, except for soils NM9 (because they are high in elevation with respect to the rest of the Delta and are present near the water recharge areas of adjacent uplands), have a high mean and a high intra-variability soil salinity. Table 3.8 shows values on the area affected at different levels of soil salinity obtained from combining the datasets in Plate 3.2 and 3.4.

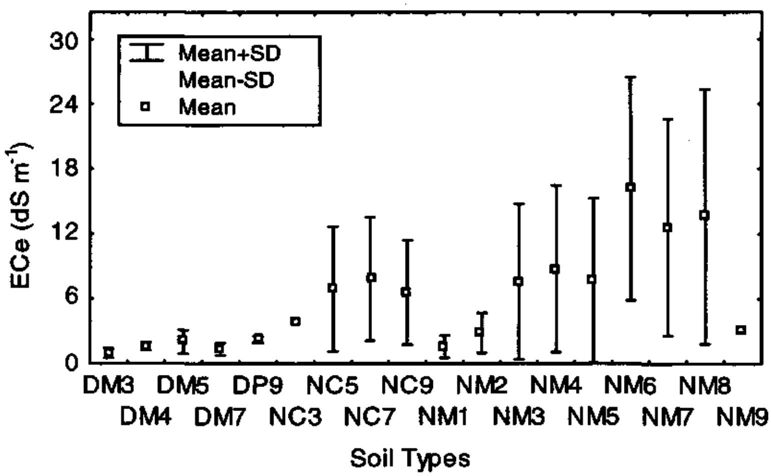

Fig. 3.4. Soil salinity (EC_e; averaged from 0 to 120 cm) of the various soil types.

Table 3.8. Soil types and soil salinity, EC_e (dS m^{-1}) between 0 and 120 cm, distribution in hectares on the study area.

	0-4	4-8	8-12	12-16	16-24	24-30	Total
NM1	170						170
NM2	875.2	24.2	6.0	.4			906
NM3	350.9	123.1	61.2	37.2	35.3		608
NM4	999.5	175.7	150.7	61.6	39.9		1427
NM5	1033.8	132.4	65.2	69.9	74.2	.7	1376
NM6	221.7	121.8	34.9	24.4	38.6	.6	442
NM7	281.5	168.1	100.7	50.2	85.7		686
NM8	353.6	212.1	138.3	84.2	176.7	13.9	979
NM9	813.9	19.9					834
DP9	101.1	12.0	2.1				115
NC3	218.0	35.4	20.2	8.5	1.2		283
NC5	270.2	106.2	23.6	2.9			403
NC7	742.6	255.4	57.9	18.8	12.0		1087
NC9	282.9	91.1	24.7	9.1	.3		408
DM3	317.4						317
DM4	87						87
DM5	24.5	.5					25
DM7	71						71
Total	7215	1478	686	367	464	15	10224

3.3.2.3. Drainage conditions

This dataset is presented as Plate 3.5. It shows how the well drained soils are near the river and in the high elevation areas. Poorly drained soils are found mainly in the coastal areas, near the adjacent uplands due to seepage and in the depression zones such as old river courses and lagoon basins.

3.3.2.4. Clay/sand content of the epipedon

Plates 3.6 and 3.7 present continuous datasets of clay and sand content in the topsoil (approx. 35 cm). High sand percentages predominate in the coastal belt and partly on the levees of the present and old river banks. High clay percentages predominate in the depression zones such as floodplain, backswamp and old river courses.

3.3.2.5. Clay content between 40-60 cm and 80-100 cm

Plates 3.8 and 3.9 show datasets of clay at 40-60 cm and 80-100 cm, respectively, in the study area. High clay percentage are found beneath the depression zones. Levees and coastal areas present low clay content down to 100 cm. In addition, the clay content is higher on the dataset at 80-100 cm than on the dataset at 40-60 cm. Deltaic evolution is associated with (i) river progradation which gives coarsening-upwards sedimentation and with (ii) the process of infilling of the lacustrine environments and abandoned courses which give fining-upward sequences. This results indicate that in terms of extended area, river progradation contributed most to deltaic evolution.

3.4. DISCUSSION ON SOIL PROPERTIES

In terms of agricultural land-use, the main soil properties of the study area are:

- *Development.*
- *Drainage conditions.*
- *Texture of the superficial and sub-superficial horizons.*
- *Soil salinity.*

Other factors such as thickness of the fluvial sediments, elevation, depth of the groundwater level or oxidation/reduction conditions are not directly significant (for agricultural purposes) in itself, but instead because they affect the above stated soil properties. The relation between soil types and geomorphology is discussed in this section, because it relates to the spatial variation of soil properties.

3.4.1. Soil geomorphology

Deltaic plains have several subdivisions (Lewis and MacConchie, 1994). Table 3.9 presents the sedimentary environments (Maldonado, 1975; Daniels and Hammer, 1986) in the study area and its relation to the distribution of the various soil types.

Table 3.9. Geomorphology of the study area and main soil types.

Soil Types	Physiographic unit	Sedimentary environments	
NM1, NM2, NM3	Deltaic plain	Fluvial	- Natural levees
NM4, NM5, NM6			- Point bars
NM3, NM4, NM5			- Crevasse (Splay/Delta)
NM6, NM7, NM9			- Floodplain / Backswamp
NM8			- Abandoned river channels
DM3,DM4,DM5,DM7,DP9			- Valley floor
Miscellaneous		Paludal	- Lagoons
NM8			- Marshes
NC3, NC5			- Sandy flats
Miscellaneous			- Tidal channels
NC7, NC9		Fluviomarine	- Delta front
Sandy undifferentiated		Holomarine	- Beaches
Sandy undifferentiated			- Sand bars

The Ebro River on the deltaic plain can be considered a high sinuosity single-channel system, meandering river pattern of low gradient and relative stability (Schumm et al., 1987). The most important process in the formation of deltas is a combination of deposition on the inside of river curves (point-bars) and deposition from overbank floods (Mathers and Zalasiewicz, 1994). For meandering fluvial systems, a stream model (Fig. 3.5) is well established with two main components:

(i) Lateral accretion, on point bars and levees forming fining upward sequences, e.g. soil types NM1, NM2 and NM3. Levee deposits and point bar sediments are laminated fine sand and silt that grade upward progressively into higher clay content. They are well drained and present the greatest possibilities for switching among land-use.

(ii) Vertical accretion, on flood basin units formed by superimposition of successive overbank deposits. In the study area there are basically two pure examples;

- *Old river channels and lagoons* have been infilled by vertically aggrading silt and clay forming the so-called soil type-NM8. These zones have exerted an important degree of control in the deltaic evolution and drainage. Moreover, an important characteristic nowadays is their extremely high soil salinity.

- *Crevasse-splays* are channel margin deposits. These soils build upward where flood waters breach levees and spill out onto the floodplain depositing a laminated sheet of silt and clay. Valley floor, floodplain and backswamps have fine-grained deposits that gradually build-up during successive flooding (soil type-NM9).

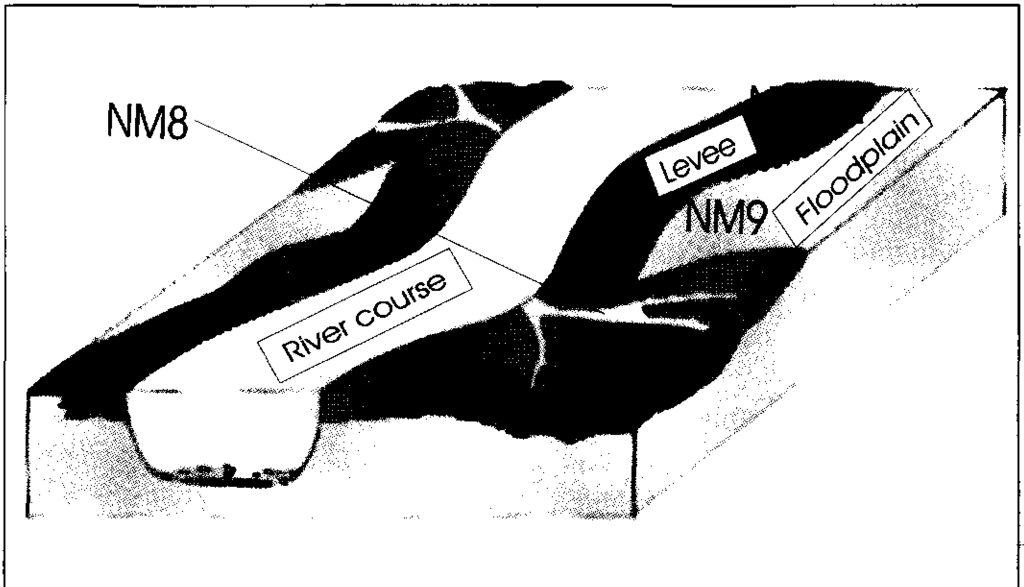

Fig. 3.5. Meandering stream model (from Mathers and Zalasiewicz, 1994) in relation to various soil types in the study area.

Variation in the ratio of vertical to lateral deposits reflects the proportion of suspended load as opposed to bedload transported, a basic feature of Schum's classification. This ratio is, in turn, a function of source proximity, for the proportion of bedload tends to decrease with distance travelled. Texture of the splays depends upon the energy of the environment and the size of the material in the system at the time of the flooding. Additionally mean sediment diameter of splays decreases away from the eroded gap. Overbank deposits away from the channel may grade laterally into clayey sediments. The "topo-sequence" soil types NM4-NM5-NM6-NM7 is a good example of this grading in sediments and geomorphology. These soils are the most frequent in the Ebro Delta and may be located in any landform. The sediments have abrupt textural changes, such as fine over sandy, if near the present coastline. The start of the new cycle results from meander cut-off. Abandoned channels are gradually filled by vertical accretion deposits during floods. A sandy wedge forms at the head of the abandoned course as the channel becomes plugged with sand just downstream from the point of diversion. Another plug of sand blocks the mouth of the channel. The formed plugs of silt and clay which are relatively resistant to subsequent lateral erosion exert an important degree of control on the location of the meander belt.

In addition, nearly level coastal plains can have large areas of uniform materials because the depositional environment (tidal range of 0.4 m is recorded in the study area) created similar conditions over a large area. Wave energy and longshore currents mobilize the channel sands (marine reworking of sediments) and transport them in the direction of the longshore drift. The large sub-area between the east coast and the inner lagoon is dominated by sand as well as the north belt surrounding the bay (soil types NC5,7,9). The epipedon texture is much finer if it is originated from fluviatile sediments. Furthermore, sediments of prograding deltas coarsen upward (fine silty over fine, coarse loamy over fine silty, sandy over fine) as the environment changes from prodelta through to interdistributary environments. Such particle-size classes are common in localized places associated with soil types NM4-NM5-NM6-NM7.

DM3-DM4-DM5-DM7 and DP9 type of soils are found in the older part of the deltaic plain, within the transition zone to the adjacent uplands. They represent only about 5% of the deltaic plain. They have been created from overbank flow of very fine materials into the valley floor. They show certain development and have high organic matter in their profile.

3.4.2. Development

The profile development criteria used (Table 3.4) is an indicator of soil genesis as well as of soil rooting conditions. Soils in the larger part of the study area, in fact the present (or subrecent) Delta, have a none or slight developed structure where:

(i) soil horizons maintain the major properties of the original material, and much of soil variability reflected parent material variability (in particular lamination was observed in the levees of the river near the mouth), and
(ii) only the epipedon had a slight development of soil structure.

These facts pose a limitation to root penetration which is not so important under present rice cultivation but could be important for other potential land-uses. This is partly due to their young age and partly to the waterlogging which prevents development of soil structure by wetting-drying. There has been also a strong influence of human activity:

(i) filling up of lagoons and old river courses or channels,
(ii) soil transportation, and
(iii) a prolonged rice management that induces the creation of a slowly permeable layer between 25-35 cm from the mineral soil surface.

The soils of the, and near the, continental shelf (units DM3-5, DM7, DP9) show calcium carbonate redistribution in the profile in the forms of nodules (calcic endopedions), generalized accumulation (hypercalcic endopedions) and hardly cemented horizons (petrocalcic horizons). The soils of the study area, in general, are calcareous throughout the profile, with an average of 36% calcium carbonate equivalent. Another form of soil development considered was the presence of organic soil materials which qualify in some cases for a histic diagnostic horizons (SSS, 1992).

3.4.3. Drainage status

Drainage is very important in such a flat coastal area, and therefore a system to quantify drainage status was developed as shown in Fig. 3.3. Poor drainage conditions were associated with a high or shallow groundwater table (Bayó et al., 1992) and continuous rice cultivation (Moorman and Van Bremen, 1978). When soil drainage conditions became poorer (from drainage class 1 to 9 of Fig. 3.3), first redoximorphic features were observed, followed by reducing conditions and, finally, matrix colours of low chroma (approx. 0). Aquic conditions were identified by the occurrence of both:

(i) Presence of redoximorphic features. They are formed by the processes of reduction, translocation and oxidation of Fe and Mn oxides. As soils were saturated and reduced for longer periods;
 - the amount of Fe depletions (chroma < 2) increased relative to the amount of Fe concentrations (chroma > 6).

- the concentrations and depletions occurring along ped surfaces and matrix, increased relative to the amount occurring around root channels.

(ii) Reduction confirmed by the dye test of α,α'-dipyridyl for Fe^{+2}.

The depth of saturation was very dynamic and was not considered useful for quantifying drainage status.

Drainage conditions were related to elevation, sub-superficial texture and nearness to water recharge areas. Poor drainage conditions limit land-use by creating a reduced environment, low O_2 concentration in the top-soil, that hampers root conditions. The high groundwater table is due to the absence of a gradient or natural drainage that would facilitate the discharge to the sea, as it happens for example in the delta of the Llobregat river in Barcelona (160 km north).

3.4.4. Texture of the superficial and sub-superficial horizons

The texture of the Ap is directly related to fertility issues whereas the sub-superficial texture is associated to fertility in relation with leaching, but also to drainage status and soil salinity. In coastal environments, coarse textures are often found. In fluvial environments, meandering stream models relate the texture of the sediments to its depositional environment or landforms. As a rule of thumb, loams are found in the levees while silty clay loams and clay loams are found in the river courses and depression zones. Fine textures in the soil profile are often associated with poor drainage conditions. Topsoils with high CEC (positively related to clay and silt content), values higher than 14 meq 100 g^{-1}, are significantly beneficial for rice cultivation. Soils with low CEC in the epipedon and high permissible leaching, such as NC5, NC7 and NC9, deserve a particular consideration in terms of management.

3.4.5. Soil salinity

Soil salinity is the key issue in the study area. Not really by a direct extreme influence on rice growth, but instead because it prevents the cultivation of a crop other than rice. This induces:

(i) *Rigidity in the cropping system.* The areas with non-saline soils allow crop rotation with its corresponding advantages. This "flexibility", not found in the major part of the study area, is of very high value.

(ii) *Recharge of the groundwater.* Approximately 4000 litres of fresh irrigation water are used per kg of rice produced.

Results of the saturated paste showed that Na^+ and Cl^- in first terms, plus Mg^{2+} and SO_4^{2-} were highly correlated with the electrical conductivity. None of the soils had a pH of the saturated paste above 8.5, so they were not alkaline. A significant relation was found between pH of the extract at saturated paste (pH_p) and at 1:2.5 dilution ($pH_{1:2.5}$).

$$pH_p = 0.913 \times pH_{1:2.5} \qquad (n=42,\ r^2_{adj}=0.78) \qquad \text{(Eq. 3.3)}$$

The results of the soil salinity analysis were summarized in the classification of salt-affected soils (Richards, 1954) shown in Fig. 3.6. The sodium adsorption ratio (SAR) and the exchangeable sodium percentage (ESP) are approximately equal for SAR values between 2 and 30. The basic four groups were:

None-saline soils, as the NM1,2,9, DM3,4,5,7, NC3 and DP9. They usually have a high relative elevation with respect to the rest of the Delta.

Saline soils are found in the low range of the saline-sodic soils. They are either (i) NC5,7,9 that are near to the sea but instead have coarser textures down in the profile which allow high leaching of salts, or (ii) NM3,4,5 which are in the better drained of the low elevation and permissible leaching areas.

Saline-sodic soils which reach maximum values of 30 dS m^{-1} averaged over the profile to 120 cm. They are NM6,7,8. NM8-type soils, in particular, use to be old river courses and lagoons that by progressive filling up and ditching have been brought into cultivation.

Sodic soils (non-saline) are not present in the study area.

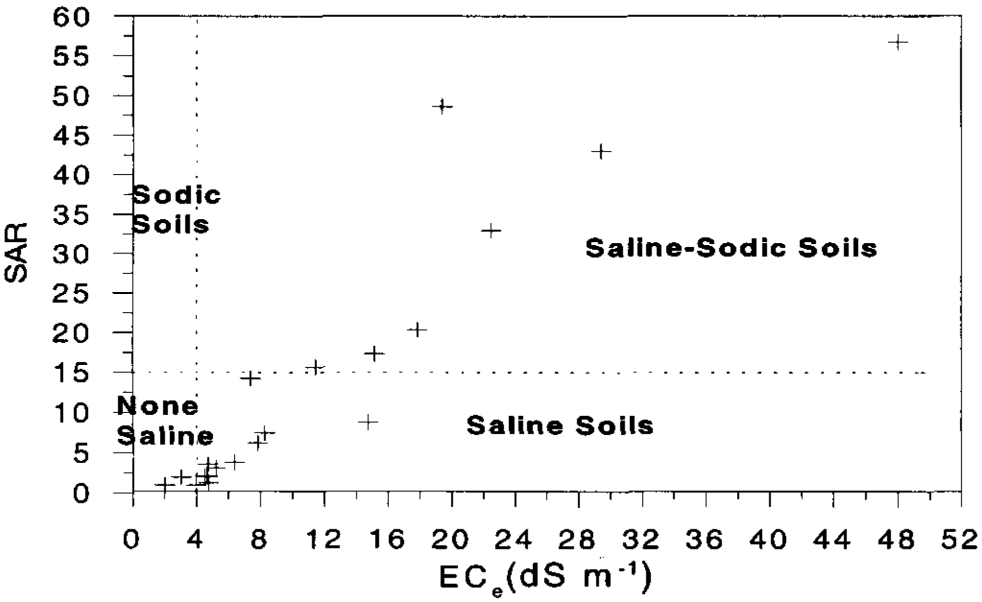

Fig. 3.6. Sodium adsorption ration (SAR) and electrical conductivity (EC_e) measured for various horizons (classified after Richards, 1954).

Groundwater analyses were performed because a significant relation between soil and groundwater salinity was expected. Equation 3.4 shows the results of the regression between the electrical conductivity of the soil saturated paste (EC_e) averaged from 0-120 cm and the electrical conductivity of the groundwater (EC_{gw})

$$EC_e = 1.98 + 0.274 \times EC_{gw} \qquad (n{=}43,\ r^2_{adj}{=}0.79) \qquad \text{(Eq. 3.4)}$$

The pH of the groundwater was on average 7.8±(2×0.2). All cations and Cl^-, as anion, were correlated with the electrical conductivity of the groundwater. SO_4^{2-} and HCO_3^-, however, saturated with the electrical conductivity at around 30 and 11 meq l^{-1} respectively. Figure 3.7 shows the scatter plot of the sodium adsorption ratio, SARgw, and the electrical conductivity, EC_{gw}, of the groundwater at various sites. Basically, three groups were distinguished:

(i) Groundwater of high EC (approx. 60 dS m^{-1}) and SAR (approx. 60) in areas which coincide with NM8-type soils (former river courses and lagoon basins).

The following two classes did not have a clear relation with soil types. Their difference, which is substantial in terms of EC and SAR, is basically a matter of proximity to water recharge areas and relative elevation to the rest of the deltaic plain.

(ii) Groundwater of medium EC (approx. 10 dS m^{-1}) and SAR (approx. 25).

(iii) Groundwater of relatively low EC (approx. 4 dS m^{-1}) and SAR (approx. 6).

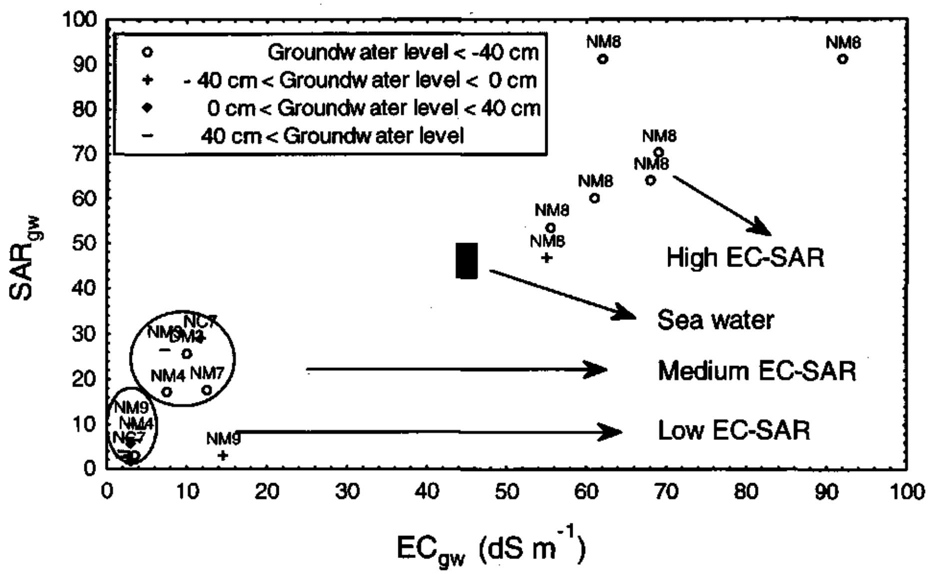

Fig. 3.7. Electrical conductivity and SAR of the groundwater at various sites on the study area. Labels correspond to the soil type where the groundwater sample was chosen. Symbols indicate the grouping of the height of the groundwater over sea level in cm computed from the digital elevation model.

These results show that in the study area the groundwater had a heterogeneous distribution. Old river courses and lagoon basins, even though small in area, form channels of groundwater with very high electrical conductivity (60 dS m^{-1}). They seemed to behave as aquicludes reaching the groundwater values of the ratio Mg^{+2}/Ca^{+2} and Cl^{-}/HCO_3^{-} of 12 and 100, respectively, whereas the average Mediterranean sea values are of 5 and 20-40 (Custodio and Llamas, 1983). These high ratios indicate that sea water, presumably, was the origin of this salinity. At the high and more occidental areas, recharge of fresh water pushed out or diluted the original saline groundwater whereas in the other areas, there was a process of salt reconcentration. Artificial drainage would be necessary for avoiding capillary rise from the groundwater in order to control salinization (Porta and Rodríguez-Ochoa, 1991). According to our results, benefits of artificial drainage such as control of soil water for better aeration, temperature and workability would be secondary factors in this study area.

3.5. POTENTIAL USE OF THE SOIL DATABASE

The soil geographical database (SGD) proved to be an outstanding tool for storing, analysing and presenting the soil data of the left bank of the Ebro Delta. The main advantage over traditional maps was its flexibility. In contrast to a "static" paper map, the SGD proved to be dynamic in terms of data management. The georeferenced data could be easily accessed. It allowed an interaction so that the information needs could be re-analysed, combined with other digital data and presented in other ways for specific users. As an example, this soil data is proposed to be combined with the irrigation scheme of the study area for improving the water management.

In this paper, the (i) object-oriented approach that produced discrete datasets and the (ii) field approach that produced continuous datasets were used for analysing and presenting the data. Within the study area, there were different geomorphological units with abrupt changes from one unit to the other. These features were better expressed in the discrete datasets. Within each geomorphological unit, there were gradual changes that were better expressed in the continuous datasets. The combination of both approaches seemed best for designing the collection, analysis and presentation of the data. Other aspects briefly discussed are:

(i) Object-oriented approach was used in this study mainly for a combination of various qualitative characteristics and nominal data such as soil classification or texture classes. The sedimentary units and its specific effects on soil types were easily delineated. Each information layer in the SGD was kept independent, while in conventional soil maps the mapping units used to be joined together. This allowed combination of the information and made it easier the treatment, interpretation and quantification of the data. Furthermore, it allowed different limits for every information layer.

(ii) Field approach was used for elevation and various soil properties relevant in the study area. This technique was most appropriate when:
- A property did not change in an abrupt way. Within a geomorphological unit, elevation as well as various simple soil properties changed gradually.
- A property was quantifiable (ordinal, interval or ratio type of attribute).
- Many observations were available. If not, so-called "eggs" came out in the datasets. The elevation dataset with 4000 observations had a better resolution than the others with 500 observations. Abrupt changes in reality, such as an old river course, were not well defined (using simply the data collected with the regular grid-survey). For defining these different units, additional short-distance measurements within them would be necessary.
- Various levels of resolution and complexity wanted to be compared. It allowed the possibility of different interpolation procedures depending on the resources available.

3.6. CONCLUSIONS

This chapter studied the soil distribution on the left bank of the Ebro Delta and developed a soil geographic database for storing, analysing and presenting the data. Based on this study, the following conclusions can be drawn:

(1) An alternative approach, to the traditional one, proved to be adequate for surveying the soils of such an area (delta). It combined geomorphological information with grid survey and short-distance measurements.

(2) The main soil properties, in terms of agricultural land-use, in the study area were profile development, drainage status, texture and soil salinity:
   (i) Profile development occurred if a histic horizon or calcium carbonate accumulation was present within 100 cm depth. In general, soil variability reflected parent material variability.
   (ii) Drainage status (Fig. 3.3) was quantified from soil morphology and field measurement techniques.

(iii) The texture of the superficial (Table 3.2) and sub-superficial (Table 3.3) horizons showed high variability in the study area (as is commonly found in deltaic environments).

(iv) Soil salinity was considered key because forbids the cultivation, without artificial drainage, of a crop other than rice inducing a lack in crop rotation. Table 3.8 showed that 30% of the study area had an averaged EC_e (over the profile to 120 cm) higher than 4 dS m^{-1}. Maximum values of 30 dS m^{-1} were recorded, especially in the courses of old rivers and basins of old lagoons. Soil salinity was associated with sodicity and related to groundwater salinity. Groundwater salinity was found of marine origin with a progressive salt concentration in some areas and dilution or pushed away in others.

(3) The main characteristic of the soil geographic database was its flexibility in terms of data management. Each information layer (Table 3.1) stored independently with the georeferenced data and its attributes allowed quick and easy manipulation.

(4) Two different approaches were used for analysing and presenting the data: (i) object-oriented approach that produced discrete datasets and the (ii) field approach that produced continuous datasets. Different geomorphological units with abrupt changes, within the study area, were better expressed in the discrete datasets. Gradual changes, within each geomorphological unit, were better expressed in the continuous datasets.

(5) The design of a scheme a priori, that combines both approaches for collecting, analysing and presenting the data is of great help for land evaluation and land-use analysis.

3.7. ACKNOWLEDGMENTS

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Steve Mathers from the British Geological Survey, International Division, and Gerrit Epema and Johan Bouma from WAU are kindly acknowledged for their extensive review of this manuscript.

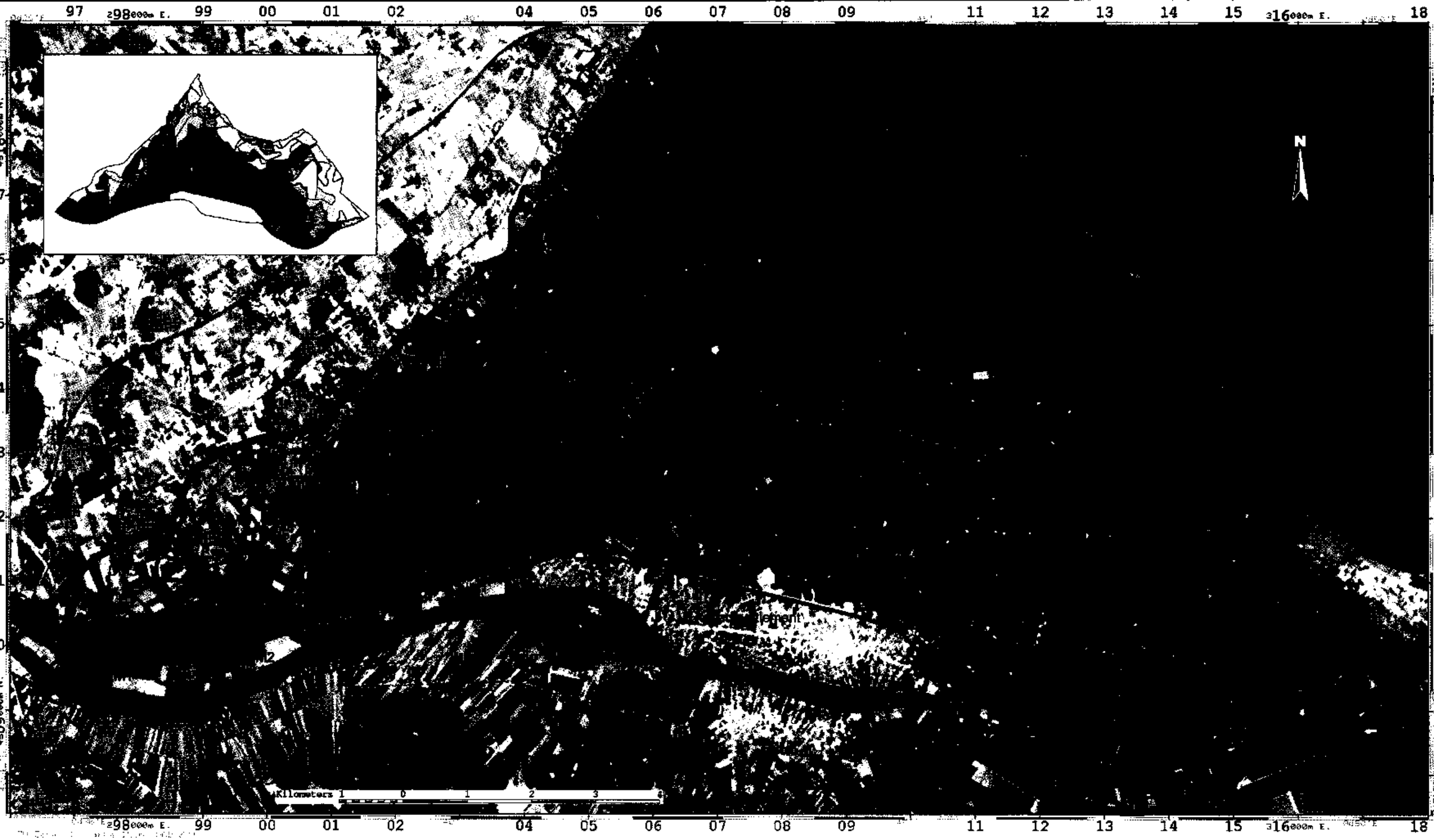

Plate 3.1. Discrete dataset of soil-type overlaying a satellite SPOT image. The scheme of the soil-type identifiers is shown in Table 3.4 and Fig. 3.3. In the top left corner of the map, a spatial distribution of the soil-types is shown as coloured polygons. These colours correspond to those of the identifiers in the dataset: green for NM1-5 (riverine soils from well to imperfectly drained), yellow for NM6-9 (riverine soils from poorly to very poorly drained), blue for NC3,5,7,9 (sandy soils), grey for DM3-5,7 (developed soils with calcium carbonate accumulation) and black for DP9 (developed soils with peat formation).

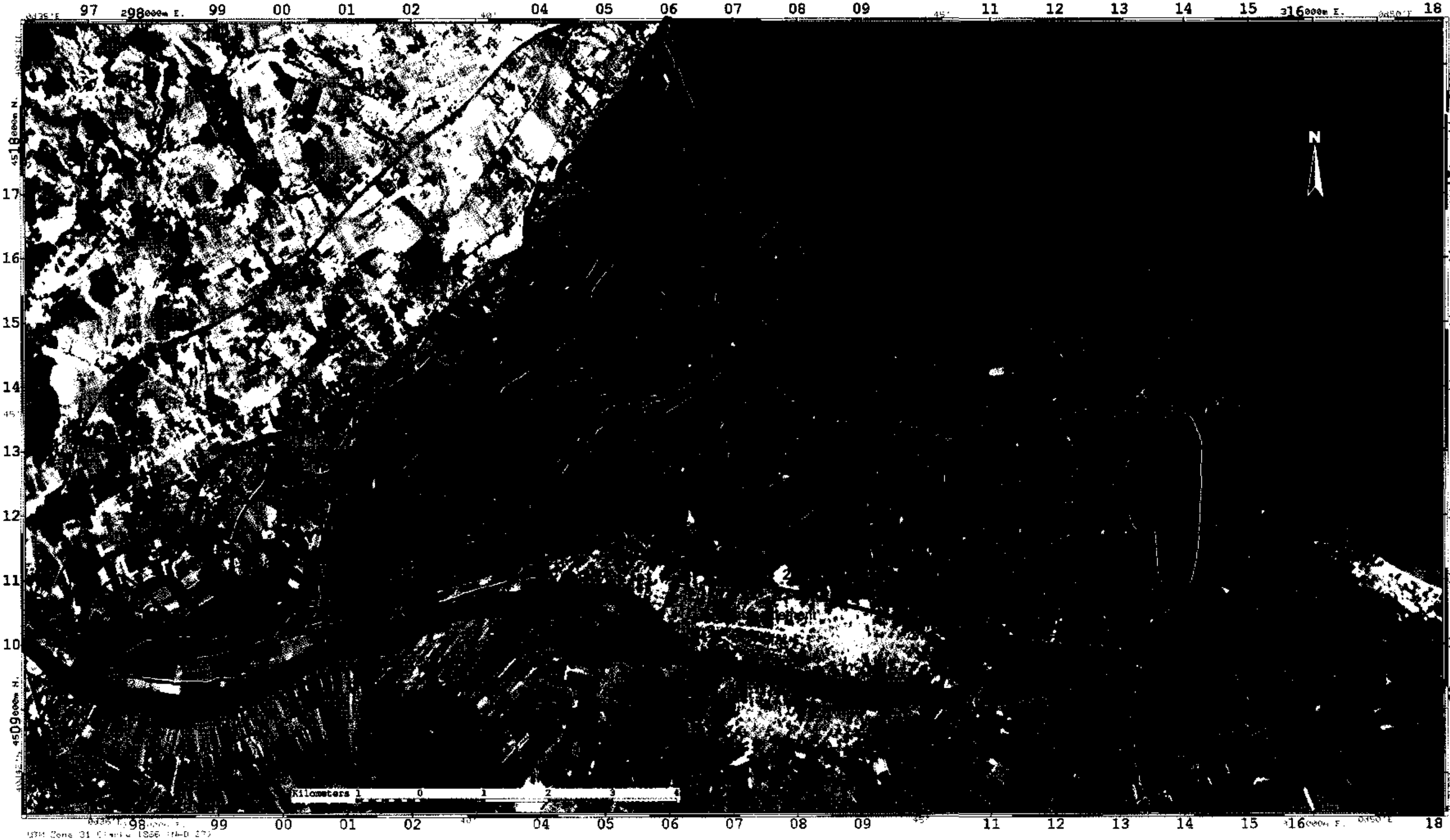

Plate 3.2. Discrete datasets of epipedon texture (0-35 cm) and particle-size class (35-100 cm) overlaying a satellite SPOT image. Lines and identifiers in yellow colour correspond to the epipedon texture (Table 3.2). Lines and identifiers in blue colour correspond to the particle-size class (Table 3.3): homogeneous classes have only one number (e.g., 0 means sandy), heterogeneous classes have two numbers (e.g., 0/1 means sandy over fine).

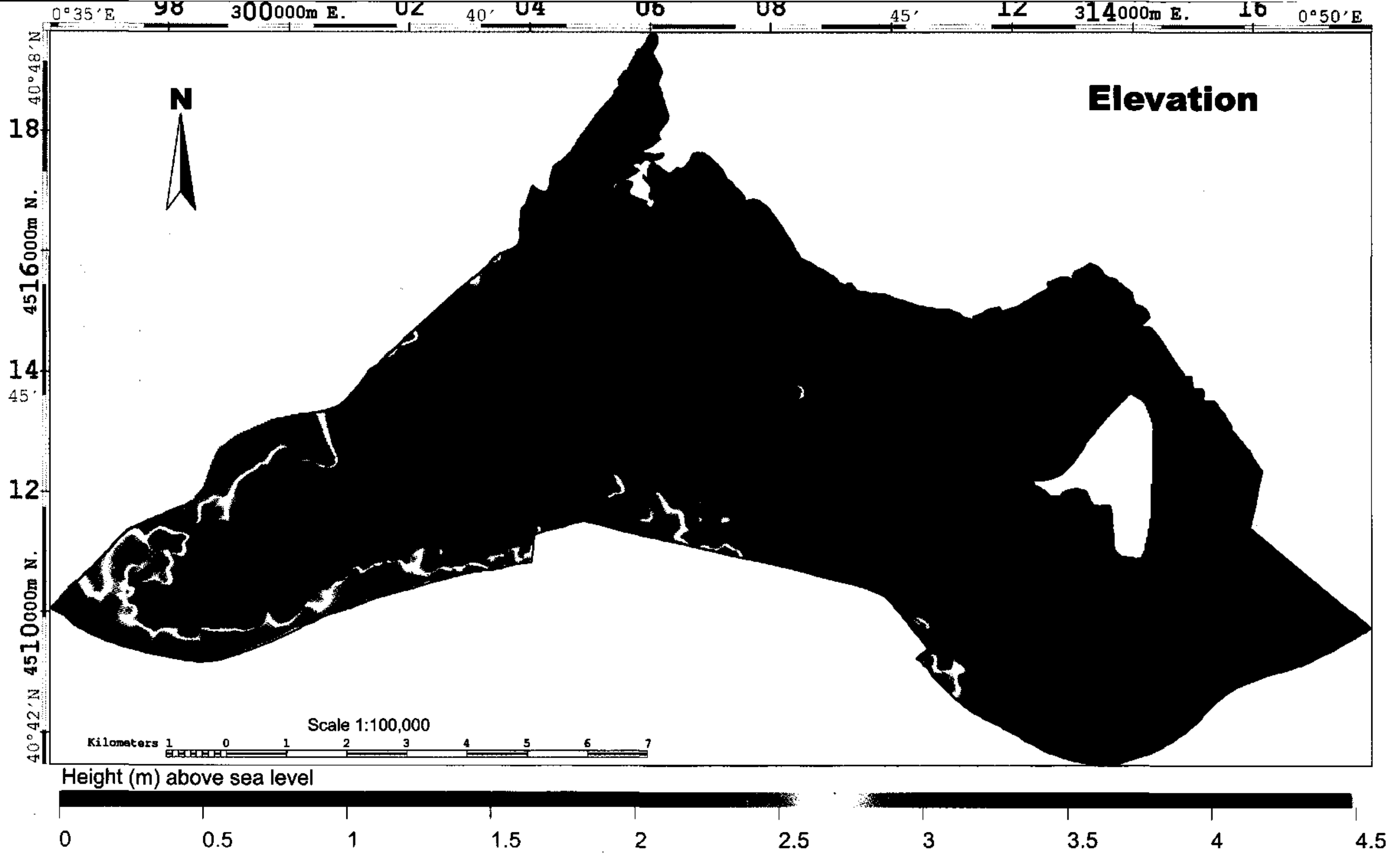

Plate 3.3. Continuous dataset of elevation (in meters above sea level).

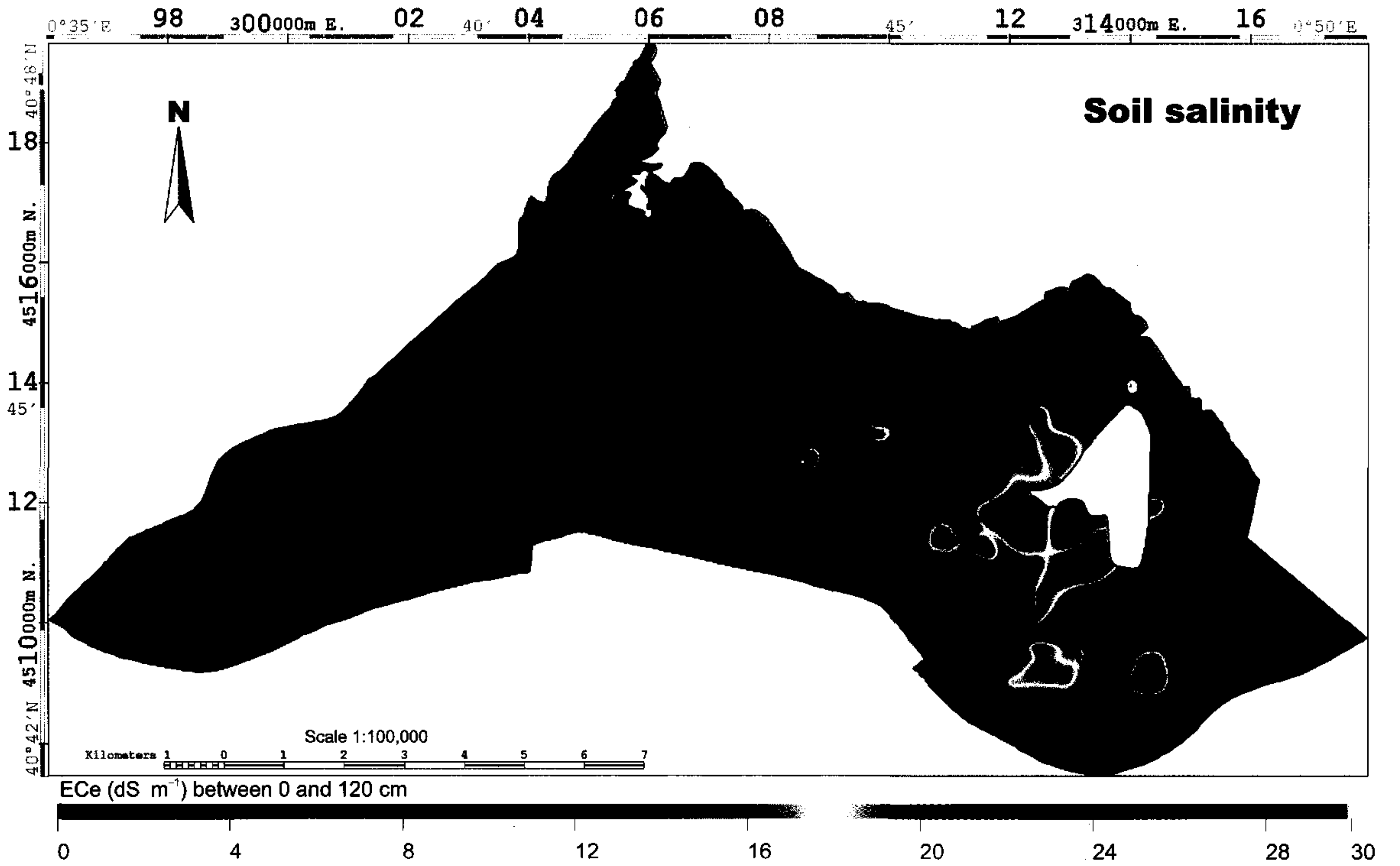

Plate 3.4. Continuous dataset of averaged soil salinity (EC_e in dS m^{-1}) starting from the surface down to 120 cm.

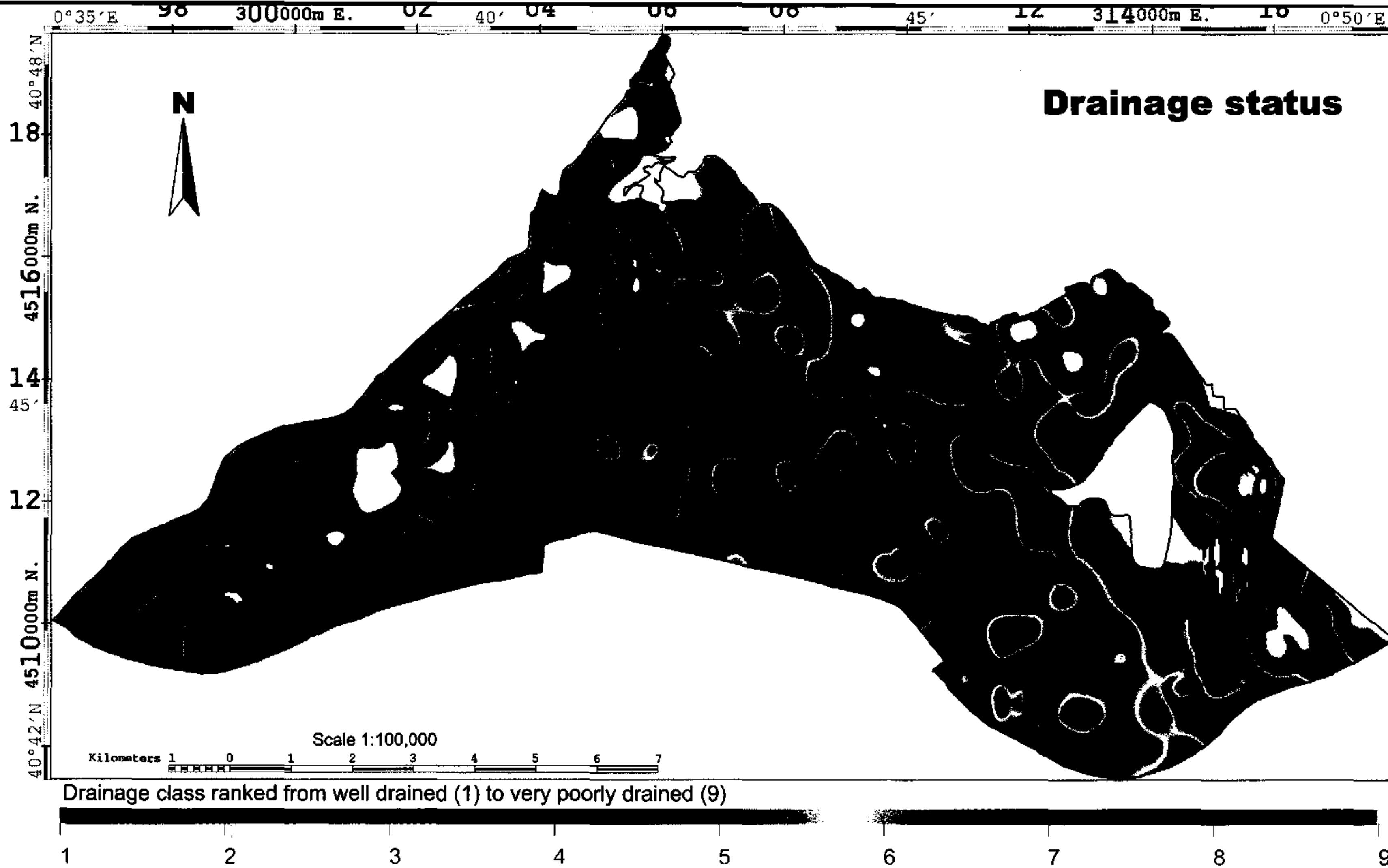

Plate 3.5. Continuous dataset of soil drainage status (quantified as shown in Fig. 3.3); numbers increase with poorer soil drainage conditions.

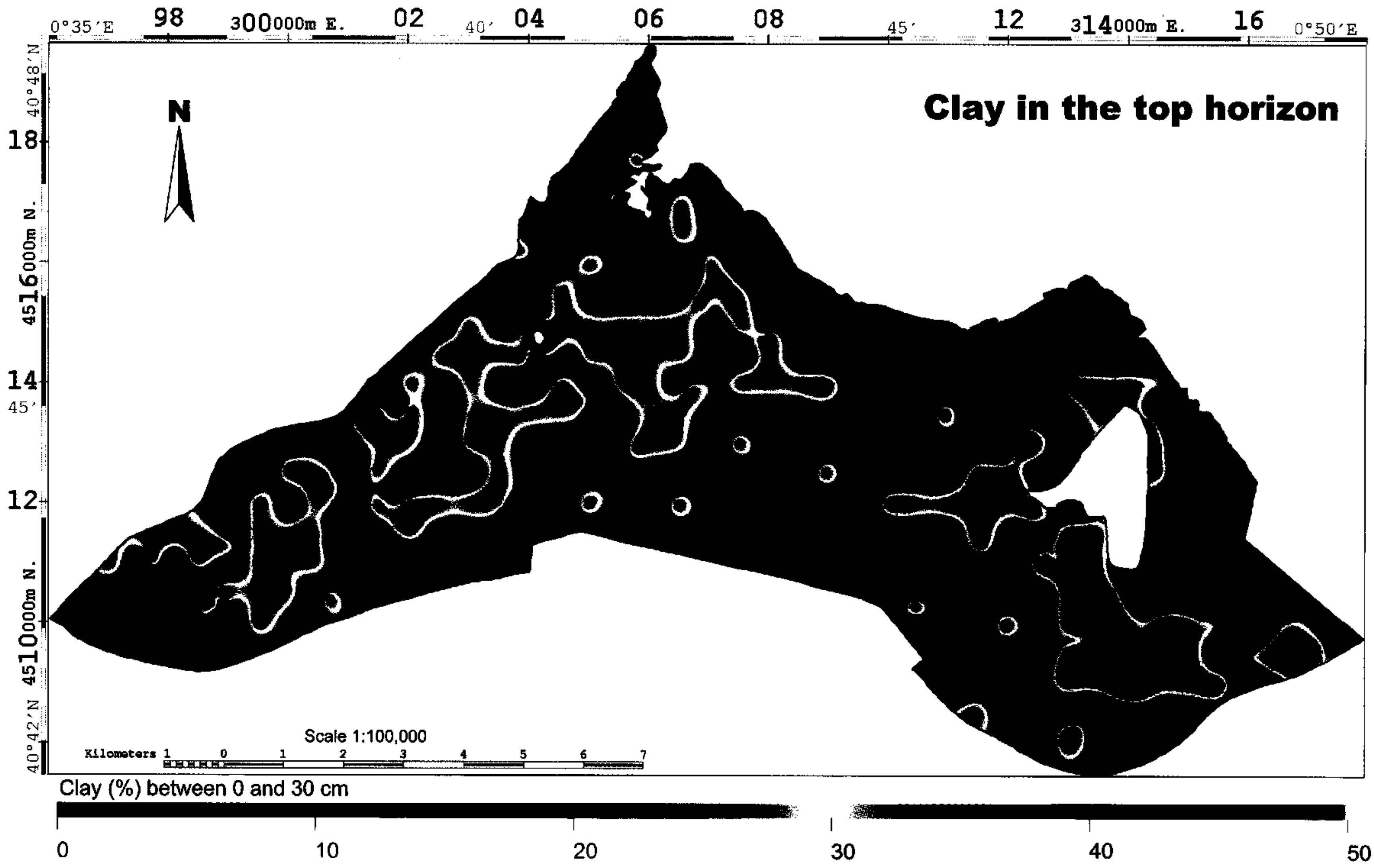

Plate 3.6 Continuous dataset of clay content in the epipedon

Plate 3.7. Continuous dataset of sand content in the epipedon.

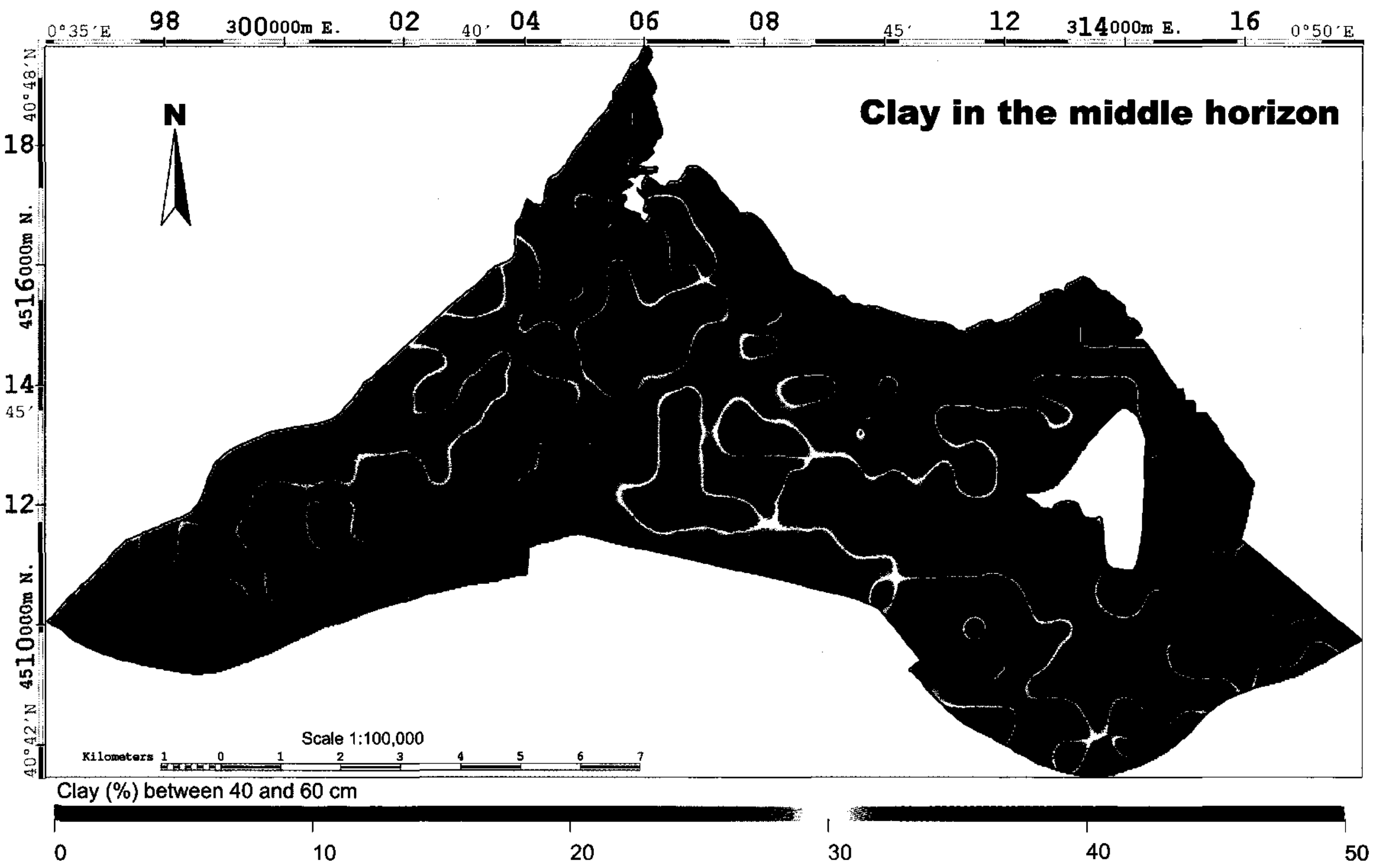

Plate 3.8. Continuous dataset of clay content between 40 and 60 cm from the mineral soil surface.

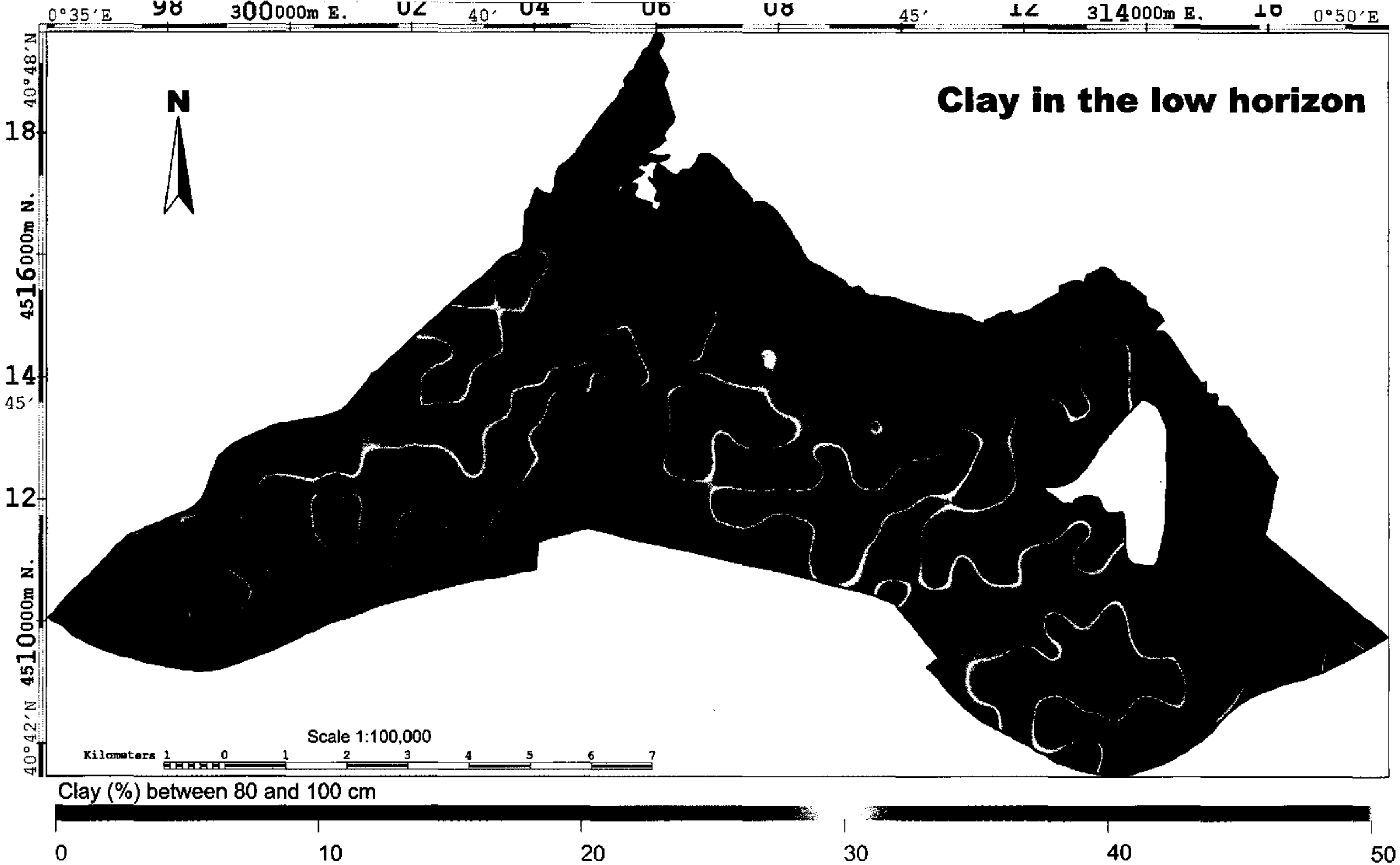

Plate 3.9. Continuous dataset of clay content between 80 and 100 cm from the mineral soil surface.

Annex 3.1. Field observed properties of the main soil types, only if their occupied surface (Table 3.6-3.8) is higher than 100 ha in the study area.

Symbol	Depth	Hor.	Oxidat./ Reduct. Status[1]	Colour matrix[2]	Oxidation mottling (%)	Oxidation colours[2]	Red. Grey mottling (%)	Red. Grey colours[2]	Red. Black mottling (%)	Red. Black colours[2]	DIPPY reaction[3]	Obs.
NM1	0-35	Ap_1	O	10YR 3/ 4	0		0		0		No	
	35-115	Bw_1	O	10YR 5/ 4	0		0		0		No	4
	115-170	$2C_1$	O	10YR 6/ 6	1-2	10YR 5/ 6	0		0		No	
	170-190	$3C_2$	O	10YR 5/ 6	1-2	7.5YR 5/ 6	0		0		No	
NM2	0-20	Ap_1	O	10YR 4.5/ 3	1-2		0		0		No	
	20-40	Apd_2	O	10YR 5/ 3	2-20	7.5YR 5/ 4	1-2		1-2		No	
	40-60	Bw_1	O	10YR 5/ 4	1-2		1-2		0		No	4
	60-105	C_1	O	10YR 5.5/ 3	2-20		0		0		No	
	105-150	$2C_2$	O/R	10YR 5/ 4	20-50	7.5YR 5/ 6	2-20	5GY 5/ 1	0		No	
NM3	0-15	Ap_1	O/R	2.5Y 4/ 3	2-20	7.5YR 5/ 6	2-20	2.5Y 5/ 1	1-2		No	
	15-30	$Apdg_2$	R/O	2.5Y 3/ 1	2-20	7.5YR 5/ 6	2-20	2.5Y 5/ 1	2-5	10BG 4/ 1	Positive	
	30-70	C_1	O/R	2.5Y 5/ 4	20-50	7.5YR 5/ 6	2-20	5Y 4/ 1	1-2		No	
	70-120	C_2	O/R	2.5Y 4/ 4	20-50	7.5YR 4/ 3	2-20	5Y 4/ 1	0		No	
	120-140	$2C_3$	O/R	2.5Y 5/ 4	20-50	7.5YR 4/ 3	20-50	5Y 5/ 1	0		No	
	140-170	$3C_4$	O/R	10YR 5/ 4	20-50	7.5YR 4/ 3	2-20	5Y 5/ 1	0		No	

NM4	0-20	Apg_1	O/R	2.5Y 4/ 3	2-20	10YR 5/ 6	2-20	5Y 5/ 1	1-2		Positive
	20-35	$Apdg_2$	R/O	2.5Y 3/ 1	2-20	10YR 5/ 6	2.20	5Y 5/ 1	2-5	10BG 4/ 1	Positive
	35-60	C_1	O/R	10YR 5/ 6	20-50	10YR 5/ 6	2-20	5Y 5/ 1	1-2		No
	60-90	C_2	O/R	10YR 5/ 6	20-50	10YR 5/ 6	20-50	5Y 5/ 1	1-2		No
	90-120	C_3	O/R	2.5Y 5/ 2.5	20-50	10YR 5/ 6	2-20	5Y 5/ 1	1-2		No
	120-150	C_4	R/O	5Y 5/ 2	2-20	10YR 5/ 6	20-50	5Y 5/ 1	2-5	N 2/ 0	No
NM5	0-20	Apg_1	O/R	2.5Y 3/ 3	2-20	10YR 5/ 6	2-5	5Y 5/ 1	0		Positive
	20-30	$Apdg_2$	R/O	2.5Y 4/ 3	20-50	10YR 5/ 6	20-50	5Y 5/ 1	2-5	10BG 1.7/ 1	High
	30-50	C_1	O	10YR 5/ 4	2-20	10YR 4.5/ 6	1-2		0		No
	50-90	C_2	O/R	2.5Y 6/ 4	20-50	10YR 4.5/ 6	2-20	2.5Y 5/ 1	0		No
	90-110	C_3	R/O	7.5Y 4/ 2	2-20	2.5Y 4/ 4	20-50	2.5Y 5/ 1	1-2		Positive
	110-130	Cg_4	R	7.5Y 4/ 1	2-20	5Y 5/ 4	>50	7.5Y 4/ 1	2-5	N 2/ 0	High
NM6	0-20	Apg_1	O/R	10YR 4/ 3	2-20	10YR 5/ 6	2-20	10Y 4/ 1	0		Positive
	20-35	$Apdg_2$	R/O	2.5Y 3/ 3	2-20	10YR 5/ 6	20-50	10Y 4/ 1	5-20	10BG 3/ 1	High
	35-50	Cg_1	R/O	2.5Y 4.5/ 2	2-20	10YR 5/ 6	20-50	10Y 4/ 1	2-5	10BG 3/ 1	Positive
	50-60	C_2	O/R	2.5Y 6/ 6	20-50	10YR 5/ 6	20-50	10Y 5/ 1	2-5	10BG 3/ 1	No
	60-80	$2Cg_3$	O/R	10YR 4/ 4	2-20	2.5Y 5/ 4	20-50	10Y 5/ 1	2-5	10BG 3/ 1	Positive
	80-140	$3Cg_4$	R/O	2.5Y 4/ 4	20-250	2.5 Y 5/ 4	2-20	10Y 5/ 1	1-2		High
NM7	0-20	Apg_1	O/R	10YR 4.5/ 4	2-20	10YR 5/ 6	2-20	10Y 4/ 1	2-5	10BG 1.7/ 1	Positive
	20-35	$Apdg_2$	R	2.5Y 4/ 3	2-5	10YR 5/ 6	>50	10Y 4/ 1	5-20	10BG 1.7/ 1	High
	35-50	Cg_1	R/0	2.5Y 5/ 3	2-20	10YR 5/ 5	20-50	5Y 6/ 1	2-5	5BG 2/ 1	Positive
	50-90	Cg_2	R	5Y 5/ 1	2-20	10YR 5/ 5	>50	5Y 6/ 1	2-5	5BG 2/ 1	High
	90-130	Cg_3	R/0	5Y 5.5/ 1	2-20	2.5Y 5/ 4.5	20-50	5Y 5/ 1	1-2		High
	130-160	Cg_4	R	5GY 5/ 1	2-20	2.5Y 5/ 4.5	>50	5Y 5/ 1	2.5	5BG 2/ 1	High

Symbol	Depth	Hor.	Oxidat./ Reduct. Status[1]	Colour matrix [2]	Oxidation mottling (%)	Oxidation colours [2]	Red. Grey mottling (%)	Red. Grey colours [2]	Red. Black mottling (%)	Red. Black colours [2]	DIPPY reaction[3]	Obs.
NM8	0-25	Apg_1	R/O	2.5Y 4/ 4	2-5	10YR 5/ 6	20-50	5GY 4/ 1	2-20	N 2/ 0	Positive	
	25-35	$Apdg_2$	R	N 2/ 0	0		>50	5GY 4/ 1	20-50	N 2/ 0	High	
	35-45	Cg_1	O/R	5Y 4/ 1	20-50	10YR 4/ 5	20-50	5GY 5/ 1	1-2		Positive	
	45-60	Cg_2	R	7.5Y 5/ 1	2-5	2.5Y 5/ 6	>50	5GY 5/ 1	20-50	10BG 4/ 1	High	
	60-80	Cg_3	R	7.5Y 5/ 1	2-5	2.5Y 5/ 6	>50	5GY 5/ 1	20-50	10BG 4/ 1	High	
	80-110	Cg_4	R	2.5Y 5/ 3	2-20	2.5Y 5/ 6	20-50	5GY 5/ 1	2-20	10BG 4/ 1	High	
NM9	0-25	Apg_1	R/O	2.5Y 3/ 3	2-20	10YR 6/ 6	2-20	5GY 4/ 1	2-20	5BG 2/ 1	High	
	25-35	$Apdg_2$	R	5Y 4/ 1	1-2		>50	5GY 4/ 1	2-20	5BG 2/ 1	High	
	35-55	Cg_1	R	5Y 5/ 1	1-2		20-50	5Y 4/ 1	1-2		High	
	55-80	Cg_2	R	7.5Y 4/ 1	2-20	5Y 6/ 4	20-50	5Y 3/ 1	1-2		High	
	80-100	Cg_3	R	7.5Y 5/ 1	1-2		>50	5Y 6/ 1	2-5	5BG 2/ 1	High	
DP9	0-15	Apg_1	O/R	2.5Y 3/ 3	2-20	10YR 5/ 6	2-20	5GY 4/ 1	1-2		Positive	
	15-30	$Apdg_2$	R/O	10Y 4/ 1	2-20	10YR 5/ 6	20-50	5GY 4/ 1	5-20	5BG 2/ 1	High	
	30-70	Cg_1	R	10Y 5/ 1	1-2		>50	5Y 3/ 1	2-5	5BG 2/ 1	Positive	
	70-90	Cg_2	R	7.5Y 5/ 1	2-20	5Y 6/ 4	>50	5Y 3/ 1	1-2		Positive	
	90-160	H	R	5BG 2/ 1								4
NC3	0-20	Apg_1	O/R	10YR 5/ 4	2-20	10YR 5/ 6	2-20	5GY 4/ 1	2-5	10BG 1.7/ 1	Positive	
	20-37	$Apdg_2$	R/O	2.5Y 3/ 2	2-20	10YR 5/ 6	20-50	5GY 4/ 1	5-20	10BG 1.7/ 1	Positive	
	37-90	$2C_1$	O	10YR 5/ 3	20-50	5Y 4/ 4	0		0		No	
	90-100	$2C_2$	O/R	10YR 5/ 2	2-20	5Y 4/ 4	2-20	5GY 4/ 1	0		No	

NC5	0-5	Apg$_1$	O/R	2.5Y 4/ 2	2-20	10YR 5/ 6	2-20	5GY 4/ 1	2-20	N 2/ 0	Positive	
	5-20	2Apg$_2$	O/R	2.5Y 4/ 3	2-20	2.5Y 5/ 5	2-20	5GY 4/ 1	2-20	N 2/ 0	Positive	
	20-35	2Cg$_1$	O/R	2.5Y 4/ 3	2-20	2.5Y 4/ 4	20-50	5GY 4/ 1	0		Positive	
	35-60	2C$_2$	O	10YR 5/ 3	20-50	5Y 4/ 4	2-20	5GY 4/ 1	0		No	
	60-80	2Cg$_3$	R	5Y 6/ 1	2-5	5Y 4/ 4	2-20	5GY 4/ 1	0		High	
	80-100	2Cg$_4$	R/O	2.5Y 6/ 3	2-20	5Y 4/ 4	2-20	5GY 4/ 1	0		Positive	
NC7	0-20	Apg$_1$	O/R	2.5Y 4/ 4	2-20	10YR 5/ 6	2-20	5GY 4/ 1	2-20	10BG 1.7/ 1	Positive	
	20-30	Apg$_2$	R	2.5Y 4/ 3	2-20	10YR 5/ 6	20-50	7.5Y 4/ 1	2-20	10BG 1.7/ 1	High	
	30-60	2Cg$_1$	R/O	5Y 5/ 2	2-20	5Y 4/ 4	20-50	7.5Y 4/ 1			Positive	
	60-90	2Cg$_2$	R	7.5Y 5/ 1	1-2	5Y 4/ 4	>50	7.5Y 5/ 1			High	
NC9	0-20	Apg$_1$	O/R	2.5Y 5/ 4	2-20	2.5Y 5/ 6	2-20	5GY 4/ 1	2-20	10BG 1.7/ 1	Positive	
	20-40	Cg$_1$	R	N 4/ 0	1-2		>50	5GY 3/ 1	20-50	10BG 1.7/ 1	High	
	40-100	Cg$_2$	R	2.5Y 6/ 1	0		>50	5GY 3/ 1	2-5	10BG 1.7/ 1	High	
DM3	0-25	Ap$_1$	O	10YR 3/ 3	2-20	10YR 4/ 2	1-2		1-2		No	
	25-45	C-B$_1$	O/R	2.5Y 3/ 2	2-20	10YR 5/ 6	20-50	5GY 4/ 1	1-2		No	
	45-70	C-Bg$_2$	R/O	5Y 3/ 1	2-5	2.5Y 5/ 6	>50	5Y 4/ 1	1-2		Positive	
	70-90	Bkn	R	5Y 3/ 1	1-2		>50	5Y 3/ 1	0		Positive	[4,5]
	90-105	2Bkm										[4]

[1] Oxidation/reduction status of the matrix: O= oxidized matrix, O/R= oxidized matrix but with some reduction, R/O= reduced matrix but with some oxidation, R= reduced matrix.

[2] Colours were recorded in the moist condition as given in the Munsell Soil Colour Charts (using the hue, value/ chroma).

[3] DIPPY designates the α,α'-dipyridyl test for ferrous iron (Childs, 1981), which was used to confirm the existence of reducing conditions.

[4] Horizon with some structure development.

[5] 2.20% calcium carbonate nodules (between 2-20 mm diameter), or poligenic graves with geopital cementation.

Annex 3.2. Laboratory (physical and chemical) measured properties of the main soil types, except soils DM4, DM5 and DM7, in the study area.

Symbol	Depth (cm.)	$pH_{(1:2.5)}$	$CE_{(1:5)}$ (dS/m)	Org.M. (%P/P)	$P_{avail.}$ (ppm)	$K^{+}_{excha.}$ (ppm)	T.Carb (%P/P)	Bulk Density (kg/m^3)	0.5<D<2 (%P/P)	0.05<D<0.5 (%P/P)	0.002<D<0.05 (%P/P)	D<0.002mm (%P/P)
NM1	0-35	7.87	0.43	1.97	27	157	34.6		0.31	47.01	36.98	15.7
	35-115	8.06	0.42	0.62			36.4		0.2	21.85	61.51	16.44
	115-170	8.67	0.15	0.16			30.0		3.03	3.49	93.47	0.01
	170-190	8.3	0.24	0.63			40.9		0.2	2.25	65..37	32.18
NM2	0-20	7.87	0.57	2.36	34	126	37.9	1333.2	0.1	19.69	52.53	27.68
	20-40	8.2	0.33	1.09	5.3	85	36.8	1763.9	0.01	6.76	62.0	31.23
	40-60	8.44	0.22				35.9	1482.5	0.01	18.74	68.71	12.54
	60-105	8.38	0.24				36.8	1504.9	0.01	21.21	66.85	11.93
	105-140	8.51	0.19				37.8	1603.7	0.01	3.98	75.48	20.53
NM3	0-15	7.82	0.74	3.26	26	149	35.34		0.32	6.11	62.62	30.95
	15-30	8.01	0.54	2.37	19	157	35.74		0.32	6.11	62.62	30.95
	30-70	8.43	0.23	0.84			35.26		0.01	5.92	70.09	23.98
	70-120	8.44	0.24	0.57			36.07		0.01	8.15	68.41	23.43
	120-140	8.64	0.2	0.29			36.39		0.01	76.58	17.97	5.44
	140-170	8.51	0.2	0.45			37.01		0.01	23.62	63.08	13.29
NM4	0-20	7.65	1.29	4.67	30	224	29.54	1437.0	0.11	3.98	58.88	37.03
	20-35	8.15	0.53	1.51	8.5	270	32.23	1624.4	0.11	3.98	58.88	37.03
	35-60	8.16	0.59				33.6	1629.3	0.0	0.41	53.06	46.53
	60-90	8.32	0.38				35.43	1618.1	0.01	2.25	72.84	24.9
	90-120	8.47	0.27				34.1		0.01	18.29	66.26	15.44

NM5	0-20	7.85	0.84	3.24	14	95	36.14	1518.9	0.01	6.92	68.11	24.96
	20-30	8.39	0.24	0.97	2.4	53	38.04	1720.1	0.01	6.92	68.11	24.96
	30-50	8.45	0.21				36.09	1556.0	0.01	13.52	65.45	21.02
	50-90	8.49	0.21				34.79	1466.8	0.01	34.28	52.66	13.05
	90-110	8.31	0.27				37.29		0.01	61.31	31.52	7.16
	110-130	8.04	0.95				36.35		0.01	25.87	59.98	14.15
NM6	0-20	7.78	1.18	3.59	25	112	36.63		0.11	24.31	51.75	23.83
	20-35	7.72	1.22	3.24	21	120	36.19		0.01	23.83	53.81	22.35
	35-50	8.38	0.42				38.36		0.1	10.53	65.12	24.25
	50-60	8.69	0.38				35.06		0.01	28.27	47.05	24.67
	60-80	8.79	0.27				34.52		0.1	76.14	18.63	5.13
	80-140	8.52	0.48				36.26		0.01	12.66	73.00	14.33
	150			0.9								
NM7	0-20	7.79	1.24	3.62	30	144	35.38	1580.1	0.42	3.95	71.15	24.48
	20-35	8.05	0.72				37.21	1689.8	0.01	3.37	69.97	26.65
	35-50	8.49	0.48				37.41	1661.8	0.1	15.73	65.28	18.89
	50-90	8.67	0.44				35.38		0.1	45.10	42.82	11.98
	90-130	8.87	1.16				36.36		0.01	64.83	30.18	4.98
	130-160	8.81	0.67	0.65			36.83		0.2	1.84	70.99	26.97

Symbol	Depth (cm.)	pH $_{(1:2.5)}$	$CE_{(1:5)}$ (dS/m)	Org.M. (%P/P)	$P_{avail.}$ (ppm)	$K^{+}_{exch.}$ (ppm)	T.Carb (%P/P)	Bulk Density (kg/m^3)	0.5<D<2 (%P/P)	0.05<D<0.5 (%P/P)	0.002<D<0.05 (%P/P)	D<0.002mm (%P/P)
NM8	0-25	7.72	3.55	4.25	21	262	34.97		0.32	12.91	71.07	15.70
	25-35	7.40	12.29	22.22			24.95		0.14	11.58	59.19	29.09
	35-45	8.04	3.52				32.93		0.21	9.69	62.86	27.24
	45-60	7.93	7.52				32.94		0.41	6.63	83.50	9.46
	60-110	7.46	6.05				33.84		0.21	4.52	58.76	36.51
NM9*	0-25	7.73	0.94	5.01	46	138	35.36	1255.6	0.44	5.87	67.1	26.59
	25-35	7.98	1.09				42.06	1508.7	0.31	4.95	56.73	38.01
	35-55	8.15	0.69				40.44	1492.2	0.21	5.45	58.62	35.72
	55-80	8.22	0.60				47.99	1520.3	0.72	23.41	44.33	31.54
DP9**	0-15	7.68	1.20	6.77	5.68	153	40.49		1.33	11.41	61.89	25.37
	15-30	7.84	0.86	6.0			47.64		1.64	12.80	55.61	29.95
	30-70	7.65	1.62	6.76			53.10		3.10	20.76	68.58	7.56
	70-90	7.5	2.35	10.34			54.73		2.71	24.01	64.57	8.71
	90-160	5.92		27.78								
NC3***	0-20	7.8	0.88	3.02	38	92	35.57	1606.8	0.21	32.67	45.92	21.2
	20-37	7.93	0.77	2.05	25	77	36.69	1665.7	0.1	34.44	43.38	22.08
	37-90	8.73	0.2	0.19	1.35	17	45.18	1557.8	0.01	97.58	1.68	0.73

NC5	0-5	7.71	2.67	1.58	70	87	38.02		0.1	38.56	56.84	4.5
	5-20	7.92	0.72	1.28	12	52	31.22	1448.6	0.01	84.6	9.72	5.67
	20-35	7.89	0.89				33.38	1592.9	0.2	88.12	7.42	4.26
	35-80	8.85	0.19				39.02	1673.9	0.01	99.08	0.56	0.35
NC7	0-20	7.73	0.84	1.71	16	70	32.78		0.1	74.79	12.33	12.78
	20-30	7.84	0.82	1.47	6.88	49	31.57		0.01	74.09	11.69	14.21
	30-60	8.07	0.52				33.57		0.1	97.49	0.08	2.33
	60-90	7.85	0.81				29.36		0.01	98.18	0.19	1.62
NC9	0-20	8.06	0.61	0.69	7.84	36.41	33.11		0.01	85.56	8.54	5.89
	20-40	8.80	0.21				29.15		0.0	98.89	0.62	0.49
	40-100	8.83	0.22				30.39		0.01	99.18	0.17	0.64
DM3	0-25	7.9	0.47	3.7	8	147	45.65		1.5	6.09	56.7	35.71
	25-45	8.39	0.38	3.49			41.89		0.43	4.04	54.83	40.7
	45-70	8.08	0.41	2.74			39.81		1.16	8.99	43.91	45.94
	70-90	8.04	0.5	2.4			47.03		8.35	21.92	30.10	39.63

* The N Kjeldahl of the epipedon is between 0.2-0.3 %P/P. The N Kjeldahl of the H fibric horizons, if present, is around 0.4-0.5 %P/P.

** The N Kjeldahl of the epipedon is 0.3 %P/P. The N Kjeldahl of the H fibric horizon is 1.1%P/P.

*** The N Kjeldahl of the epipedon is 0.15 %P/P.

Annex 3.3. Chemical composition of the groundwater in the study area at various sites. One sample per main soil type (if the surface mapped is higher than 100 ha) with the corresponding UTM coordinates (m) is shown. Depth_ss corresponds to depth of the groundwater from soil surface; Depth_sl corresponds to depth of the groundwater from sea level, computed from the digital elevation model.

Xcoord. (m)	Ycoord. (m)	Soil type	Depth_ss (cm)	Depth_sl (cm)	pH	EC (dS m^{-1})	CATIONS (meq l^{-1}) Sum	Na^+	Ca^{2+}	Mg^{2+}	K^+	ANIONS (meq l^{-1}) Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}	SAR
302353	4510700	NM1	> 200	>200												
306643	4513900	NM2	145	3	8.10	2.99	32.9	16.4	5.5	10.3	.7	10.2	15.3	8.1	<.1	5.8
306131	4513400	NM3	160	-40	7.45	2.18	24.0	5.7	8.8	9.4	.1	7.9	9.5	6.7	<.1	1.9
307017	4511563	NM4	105	75	7.95	2.82	14.1	4.7	4.0	4.4	1.0	5.3	5.9	3.7	<.1	2.3
313586	4507790	NM5	130	-10	7.57	3.54	21.5	6.7	9.7	5.0	.1	7.6	9.7	5.0	<.1	2.5
310910	4509140	NM6	125	125	7.68	4.16	49.4	29.1	7.7	12.3	.3	24.7	15.8	8.5	.6	9.2
309868	4512777	NM7	155	-75	7.82	12.5	134.3	86.2	18.3	29.3	.5	116.3	19.2	3.8	.1	17.6
307041	4512289	NM8	135	-5	7.50	55.0	592.2	422.3	30.2	132.5	7.2	564.8	28.4	7.2	<.1	46.8
302053	4512596	NM9	85	45	7.82	2.83	33.9	19.1	4.6	9.6	.6	13.3	9.1	10.3	<.1	7.2
301736	4513563	DP9	30	20	7.75	2.96	14.7	3.8	8.2	2.7	.04	5.1	2.6	7.3	<.1	1.6
309613	4513393	NC3	105	-5	7.89	2.57	27.1	8.6	13.5	4.8	.2	9.6	16.0	2.2	<.1	2.8
307700	4515913	NC5	95	-50	7.99	3.50	21.3	7.8	8.4	4.9	.2	9.8	8.5	3.3	<.1	3.0
305177	4516868	NC7	70	-5	7.99	2.73	12.1	5.8	3.9	2.3	.08	5.0	4.2	3.1	<.1	3.3
314922	4513591	NC9	70	-35	8.12	3.0	16.1	7.2	4.5	4.1	.3	5.8	4.5	6.1	<.1	3.5
300715	4512233	DM3	85	65	7.77	1.7	18.5	6.4	7.5	4.5	.1	5.8	7.6	5.2	.6	2.6

Rice potential production and actual maximum levels

Abstract:
ORYZA1 (Kropff et al., 1994) is an explanatory model for simulating rice growth, development and leaf area index (LAI) under potential production. The present study aims at testing the performance of ORYZA1 for Mediterranean conditions (farming practices, cultivars, weather) for fully irrigated direct-seeded rice. ORYZA1 was calibrated and validated with field data of two cultivars, Tebre and L-202, grown during several years in the Ebro Delta (Spain). Phenological development of the rice crop, daily dry matter production and leaf area development were calibrated. Tebre and L-202 had no significant differences in the length of total development period. The pre-heading period, however, was longer and the post-heading period shorter in L-202 than in Tebre. This induced differences in translocation, spikelet number per unit area, weight of the grains and harvest index. The following crop characteristics were similar between the cultivars: extinction coefficient (it increased with development stage), dynamic nitrogen distribution, partitioning of assimilates, relative death rate of leaves, relative growth rate of leaf area during exponential growth (0.009 $(°Cd)^{-1}$ with a Tbase of 10°C), specific leaf area (between 25 and 15 $m^2\ kg^{-1}$ dry matter of leaf) and a strongly decreasing specific stem green area (between 20 and 2 $m^2\ kg^{-1}$ dry matter of stem). The best simulation was achieved when considering that leaf area index represents the leaf blade area only, with no contribution of stem green area to the photosynthesis apparatus of the rice plant. The model simulated rice growth very accurately until flowering. After flowering, however, divergences appeared and increased especially at the yellow ripe stage. From then on the crop did not grow much more, whereas it continued in the simulation. This reduction of growth rate was usually accompanied by an increase in relative death rate of leaves and drying of the grains. The main source of error may be a limited understanding of the ripening and sink limitation processes. A considerable yield gap (2000 kg ha^{-1}) between potential and actual yield remained. A climatic variability assessment over the last ten years showed a small, but similar variation (coefficient of correlation 0.7) in simulated and measured rice yields.

Keywords: Crop parameters; Growth; Development; Leaf area index; Crop model; Simulation.

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4.1. INTRODUCTION

Crop growth and development is subject to year-to-year and location-to-location variation. For better understanding, crop monitoring and yield forecasting are essential (Horie et al., 1992). Three methods are currently being developed and applied for crop monitoring and yield forecasting:

- field measurement and analyses of standing crops (Wisiol, 1987),
- application of remote-sensing technologies (Chapter 5) and,
- use of crop growth models (Goudriaan and Van Laar, 1994; Graf et al., 1990).

Crop models of various types are widely used in quantitative research in agriculture and biology (Silva, 1985). This chapter deals with an explanatory dynamic mathematical model for simulation of rice growth and development under potential production conditions. The potential yield of a rice crop is determined only by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation. The objective of this study was to calibrate and test the performance of the ORYZA1 model for direct-seeded fully irrigated rice, cultivars Tebre (Spanish) and L-202 (North-American), in a Mediterranean climate.

The general structure of the model ORYZA1 (version 1.3) is presented in Kropff et al., 1994. Under optimum growth conditions, light, temperature and varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day. Temperature, being a major difference between tropical and temperate conditions, has effects on: (i) development rate, (ii) photosynthesis, (iii) leaf area extension growth and (iv) fertility. The model follows daily dry matter production of the plant organs, and the rates of phenological development. By integrating these rates over time, dry matter production is simulated throughout the growing season. An important advantage of the current model is that it can be used to assess the impact of planting date, weather, latitude and leaf N contents measured or simulated for rice cultivars. The calibration process needed a limited number of parameters which were obtained from field data in the Ebro Delta (Spain).

The rice plant usually takes 3-6 months from germination to maturity, depending on the cultivar and the environment in which it is grown. In Europe, Australia and USA rice is commonly grown as lowland direct-seeded under fully irrigated conditions. The climate is characterised by long days, high solar radiation and relatively large diurnal temperature fluctuations (Hill et al., 1991). Compared with transplanted rice, the same varieties when direct-seeded have lower tillering and require greater N inputs to produce the same yield (Dingkuhn et al., 1991a,b). Rice in the Ebro Delta is mainly wet direct-seeded and takes between 130-150 days to reach maturity (Caballero i Lluch, 1992). Three growth phases can be distinguished in a rice crop: vegetative, reproductive pre-heading, and reproductive post-heading. The vegetative phase refers to the period from germination to the initiation of panicle primordia; the reproductive pre-heading phase from panicle primordia initiation to heading; and the reproductive post-heading phase from heading to maturity (Yoshida, 1981).

Phenological development of the rice crop, daily dry matter production and leaf area development were calibrated. Once calibrated, the model was used to analyse experimental data with measured leaf area index (LAI) or leaf nitrogen (N) content as input, as well as with LAI or time course of leaf N simulated. A calibrated model should be validated before it allows estimation of yield potential to other years. The model was validated with the 1994 and 1996 dataset. As an additional test, the model was used to predict the relative effect of climatic interannual variations in the Ebro Delta over the last ten years.

4.2. MATERIALS AND METHODS

4.2.1. Description of field and laboratory measurements

Experiments were carried out on farms in the Ebro Delta, in north-eastern Spain, in the rice growing seasons of 1994, 1995 and 1996. The farms selected had minimal limitations by water, nutrient, weeds, diseases or pests, so that production was considered to be limited only by temperature and radiation. Rice productions on these farms were the highest in the study area and clearly higher than in the experimental station.

The rice cultivars were short (Tebre) and long-B (L-202 or Thaibonnet) grain rice cultivars. The agronomic management in the 1995 rice growing season is shown in Table 4.1. Crop samples were taken at three sites within the parcels on an approximately biweekly basis during the rice growing season. A round frame of 0.5 m^2 was used for crop sampling. The rice samples were cleaned and kept cold in a portable cooler. A subsample was chosen and separated into the different components: stems, green leaves, dead leaves and grains. By rice grain is meant the true fruit or brown rice (caryopsis) and the hull, which encloses the brown rice (Yoshida, 1981). Fresh weight of the leaves, stems and grains were measured. Leaf blade area and stem green area were determined with a LI-300 Area Meter. Oven dry weight measurements were made independently for every component of the plant sample. Finally, the dry matter of leaf blade samples were analysed at the laboratory for nitrogen (Kjeldahl). A final harvest of five square meter with three replicates in every parcel was collected.

Table 4.1. Agronomic practices of the four farms during the 1995 rice growing season.

	Farm 1	Farm 2	Farm 3	Farm 4
Cultivar	Tebre	Tebre	Tebre	L-202 (Thaibonnet)
Seeding Julian Date	105	112	111	117
Seeding rate ($kg\ ha^{-1}$)	183	170	165	138
Fertilizer				
N basal ($kg\ ha^{-1}$)	152	70	42	42
P basal ($kg\ ha^{-1}$)	5	50		
K basal ($kg\ ha^{-1}$)	11	70	95	95
1°N split Ti.($kg\ ha^{-1}$)		80	84	84
2°N split PI ($kg\ ha^{-1}$)			52.5	63 & 42 (3 top dressings)
Herbicides				
Echinochloa (10-25/5)		Molinate	Molinate	Molinate
Cyperacea (10-20/6)	Bentazona	Bentazona	Bentazona	Bentazona
Fungicides				
Fungicides (18-28/ 7) (13-23/ 8) (1-10/ 9)	Carbendazima+ Mancozeb: 2 appli.	Carbendazima+ Mancozeb: 2 appli.	Carbendazima+ Mancozeb: 2 appli.	Carbendazima+ Mancozeb: 3 appli.
Harvest Julian Date	264	261	263	273

A Decagon Sunfleck Ceptometer (Model SF-80, Decagon Devices, Inc. 1989) was used to measure the photosynthetically active radiation (400-700 nm) above and below the canopy at each sampling. Daily maximum and minimum temperature and global short-wave radiation were recorded at the agricultural station of Amposta, within a radius of 10 km from the experimental farms.

In order to evaluate the model in a wide range of environmental conditions, data on phenological development and final yield were also obtained from two other sources in the Ebro Delta: the agricultural research station from the Catalan government (IRTA) and the trials done by Migjorn S.A. published in the book Caballero i Lluch (1992). The data set was split up and parameter values calibrated with the 1995 data. The calibrated model was validated with the 1994 and 1996 data set. In addition, the data set of IRTA and Caballero i Lluch (1992) was used for visualizing the correspondence between the year to year variation between the simulated potential yield and observed actual values.

4.2.2. Model description

Input requirements of the model are: latitude, daily weather data (global radiation, maximum and minimum temperature) and seeding date (no transplanting effects were considered). The model describes phenological development (Section 4.2.2.1) and growth (Section 4.2.2.2) of flooded rice crop from emergence to maturity on the basis of crop genetics properties and environmental conditions. The model simulates leaf area growth (Section 4.2.2.3) based on specific leaf area and/or temperature sum. The parameters once calibrated were inserted in the model as a constant or as a function of development stage.

4.2.2.1. Crop development calibration

The development stage (DVS) of a plant defines its physiological age. It determines the formation of the various organs and their appearance. As many physiological and morphological processes change with the phenological stage of the plant, accurate quantification of phenological development is essential in any simulation model for plant growth (Yin, 1996). Four clearly different stages are defined (Van Keulen and Seligman, 1987); seeding date (DVS=0), panicle initiation (DVS=0.65), flowering (DVS=1) and maturity (DVS=2). No photosensitivity was considered for these cultivars. Maturity stage was defined as in crop physiology, the time when the maximum grain weight is attained. This is not the same as the time of harvest, which is usually determined by farmers experience, and based on grain color and leaf senescence. The development stage of rice at every sampling time was defined according to a linear temperature sum model. According to Gao et al. (1992), for Japonica varieties the base temperature is 10°C, the optimum temperature 28°C, and the maximum 40°C. Data on sowing, flowering and maturity dates from several sources in the Ebro Delta were used for calculating the required temperature sum (TS) to reach the defined phenological stages.

4.2.2.2. Crop growth calibration

Potential production occurs in conditions with ample nutrients and soil water throughout the growth of the crop. The part in which daily dry matter production is calculated is the core of the model. Canopy photosynthesis is the leaf photosynthesis accumulated over the canopy. Leaf photosynthesis depends on the light intensity and nitrogen content. The parameterized steps are:

• CO_2 assimilation of the canopy as dependent on the light-transmission, light response-leaf photosynthesis, and leaf photosynthesis-nitrogen curve. The light transmission curve is characterized by the extinction coefficient. Thus, the extinction coefficient (K) was calibrated. The light-leaf photosynthesis curve is used to calculate photosynthesis of leaves at different depths of the canopy throughout the day. For linking the photosynthesis-nitrogen curve, the nitrogen percentage values of the green leaves were measured.

• Dry matter partitioning and mobilization. In the model, the total daily dry matter increment is partitioned to the various plant organ groups according to fractions that are a function of development stage. The model simulates a pool of reserves in the stems which are translocated to the grains after flowering.

The maintenance respiration and growth respiration modules of the ORYZA1 model were not altered (Penning de Vries and Van Laar, 1982).

(i) Light transmission.

Canopy CO_2 assimilation is influenced by the extinction coefficient (K). The ratio between transmitted and incoming photosynthetic active radiation (PAR; 400-700 nm) under a canopy decreases approximately exponentially with leaf area index (Monsi and Saeki, 1953):

$$f_{trans} = e^{-K*LAI} \qquad \text{(Eq. 4.1)}$$

where:

f_{trans} = fraction of PAR transmitted by the canopy

K = extinction coefficient.

(ii) Light-saturated leaf photosynthesis.

The maximum rate of CO_2 assimilation of a leaf is calculated from both the N content of the leaves and the average daytime temperature. The N content in the leaves is higher in the top leaves, and therefore the N profile in the canopy is taken into account. Maximum leaf photosynthesis is a linear function of surface leaf nitrogen weight, SLNW (Cook and Evans, 1983; Peng et al., 1995).

(iii) Partitioning of assimilates.

Assimilates are partitioned into roots, stems and leaves during the vegetative period. In determinate crops, the reproductive sink dominates after flowering. It is assumed that growth rate of organs is basically source-dependent; sinks accept assimilates at the rate with which they are formed. In the model, the total daily dry matter is partitioned to the various organs according to fractions that are a function of development stage, independent of the amount of available assimilates. Experimentally these fractions were derived by analysing the fractions of new dry matter production distributed to the plant organs between two subsequent harvests.

For dead leaves the increase in dry weight is difficult to measure. It is assumed that new leaf growth ceases when the maximum weight of leaves is reached, and the decline of green leaves is due to death of leaves. The relative death rate of leaves (RDR) was calculated in a simplified way from experimental data. For the time interval between two samplings, the relative death rate was calculated as follows, starting at the time when leaf dry matter was highest:

$$RDR = (\ln[DWGL]_t - \ln[DWGL]_{t+\Delta t})/\Delta t \qquad \text{(Eq. 4.2)}$$

in which t is expressed in days.

(iv) Formation and mobilization of reserves.

Mobilization is the movement of compounds from a tissue where they were deposited temporarily to where they are utilized. During the pre-heading period, the stems act as a sink, not only for its structural growth but also as a sink of stem reserves. In the post-heading period the reserves in the stems are remobilized. Transport of glucose requires only a small amount of energy. In the model, the glucose produced by mobilization is treated in the same way as glucose from photosynthesis.

(v) Sink limitation.

The sink size is computed as the number of grains multiplied by the maximum growth rate of one grain. ORYZA1 calculates the total number of spikelets by multiplying the growth of above-ground biomass in the period between panicle initiation and flowering by the spikelet growth factor, SPGF. SPGF is a calibrated variable and equal to the ratio between number of spikelets and growth of above-ground biomass between panicle initiation and flowering. The maximum growth rate of individual grains is estimated as the weight of mature grains of a cultivar, divided by half the grain filling period. Under most conditions, the grain weight when considering the full grains of field crops is a very stable varietal character (Soga and Nozaki, 1957). Crop growth and simulation stop when the weight of individual grains reaches its maximum value. The spikelet fertility module of the ORYZA1 model, based on Horie et al. (1992), was not modified.

4.2.2.3. Leaf Area Development Calibration

The green leaf area of plants determines the amount of absorbed light and thereby CO_2 assimilation. The leaf area index of a crop is the total surface of one side of green leaves per unit of soil surface. In the model, either the measured leaf area index (LAI) can be used or LAI can be simulated.

In early growth, when the canopy is not closed, the plants grow exponentially as a function of the temperature sum (TS). The temperature sum is calculated as in the crop development module.

For a closed canopy, leaf area can be derived from leaf weight using specific leaf area (SLA). SLA, being an indirect measure of leaf thickness, changes with development stage. The surface area of stems may be determined by multiplying their weight by their "specific stem green area (SSGA)".

4.3. RESULTS

4.3.1. The Calibration Procedure

4.3.1.1. Crop Development

• Development rate in the pre-heading and post-heading periods. The predictions and standard errors have been standardized (using regression techniques) by averaging over two factors; year and source of data (e.g. Caballero i Lluch, IRTA and our experimental farms). A special emphasis was made on defining the proper maturity stage moment when the maximum weight of the grains was reached. It usually coincided with a 26-25 percentage moisture content of the grain. The temperature sum from seeding to maturity, with a temperature base of 10°C, is approximately 1650 degree-days for both cultivars, so that the overall development rate is similar. The pre-heading and post-heading periods, however, are different among cultivars. The average value and standard deviation for the development rates per degree-day in the pre-heading and post-heading period are 1.033±0.014 (10^{-3} °$C^{-1}d^{-1}$) and 1.500±0.036 (10^{-3} °$C^{-1}d^{-1}$) for Tebre and 0.875±0.009 (10^{-3} °$C^{-1}d^{-1}$) and 1.933±0.048 (10^{-3} °$C^{-1}d^{-1}$) for L-202, respectively.

4.3.1.2. Dry matter production

• Extinction coefficient (K). The fraction of light transmitted was plotted against LAI using the experimental data from 1995 (Fig. 4.1), and compared to Eq. (4.1) for the

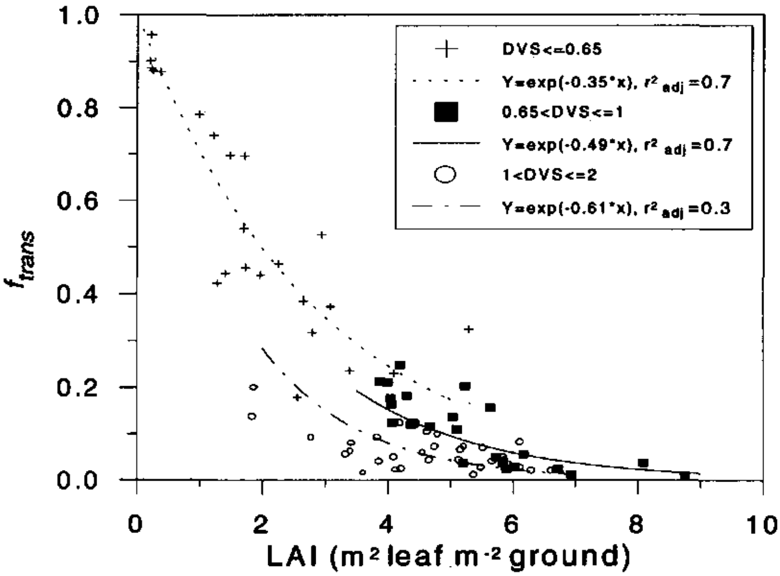

Fig. 4.1. Relationship between the values of light transmitted (f_{trans}) and leaf area index (LAI; leaf blade area) in the 1995 dataset. The functions represent the regression lines for the three different development stages.

best fitting K-values. A linear model on a log-scale, assuming a constant K, would give an overall K of 0.54. Figure 4.1, however, shows that the extinction coefficient is not constant and increases with development stage. The result of the calibration of the extinction coefficient, differentiating the three clearly defined development phases, is illustrated in Fig. 4.1. The scattering in the data is greatest at the last development phase, probably because yellow (senesced) plant material was present in most experiments and the canopies were lodged to some degree.

• Decline of nitrogen over time. The N content of green leaves during the rice growing seasons is shown in Fig. 4.2(a). SLNW dynamic behavior with development stage is shown in Fig. 4.2(b). Differences appear in SLNW between 1994 and 1995, indirectly related to differences in specific leaf area between both years. The solid line in Fig. 4.2b represents the calibrated values for 1995 as it was used in the model.

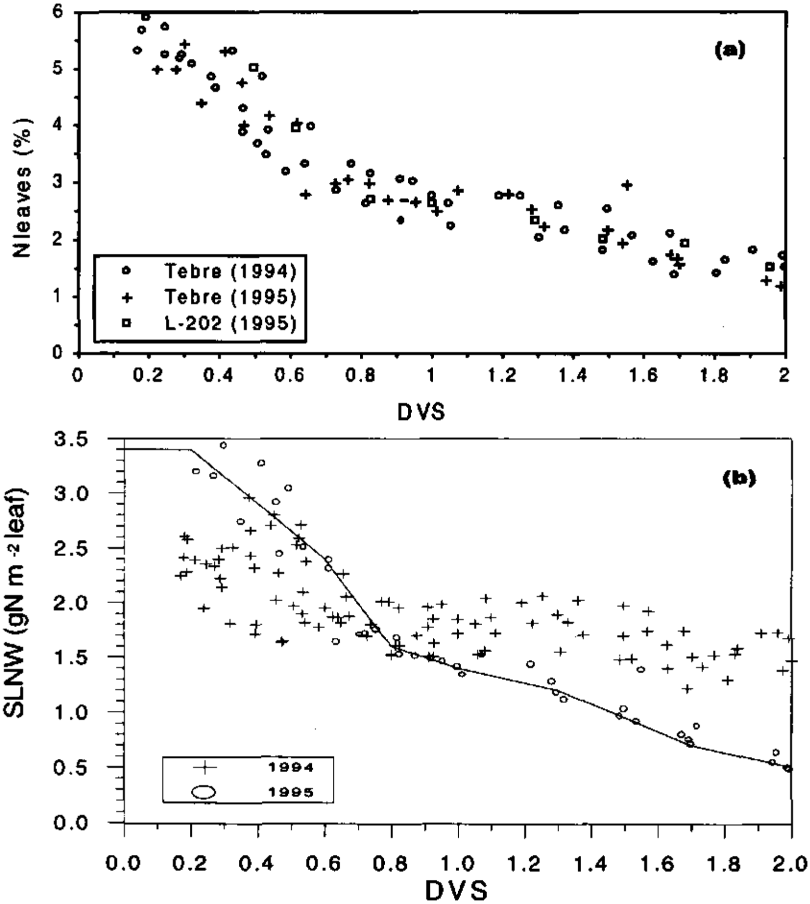

Fig. 4.2. **(a)** N content (%) of green leaves during 1994 and 1995 versus development stage (DVS), for cultivars Tebre and L-202 . **(b)** Surface Leaf Nitrogen Weight (SLNW) with development stage (DVS) in 1994 and 1995 for cultivars Tebre and L-202. The line represents the calibrated values for 1995 as it was used in the model.

• Partitioning of assimilates. The relationships used in the model are given in Fig. 4.3(a). The dry matter distribution patterns in the various experiments corresponded well with each other, indicating small management and varietal effects. The grains attract most of the assimilates after flowering, though small fractions may still go to leaves or stems. Figure 4.3(b) shows that during both seasons (1994 and 1995) a lowering of the fraction to the grain at the very last stage was observed.

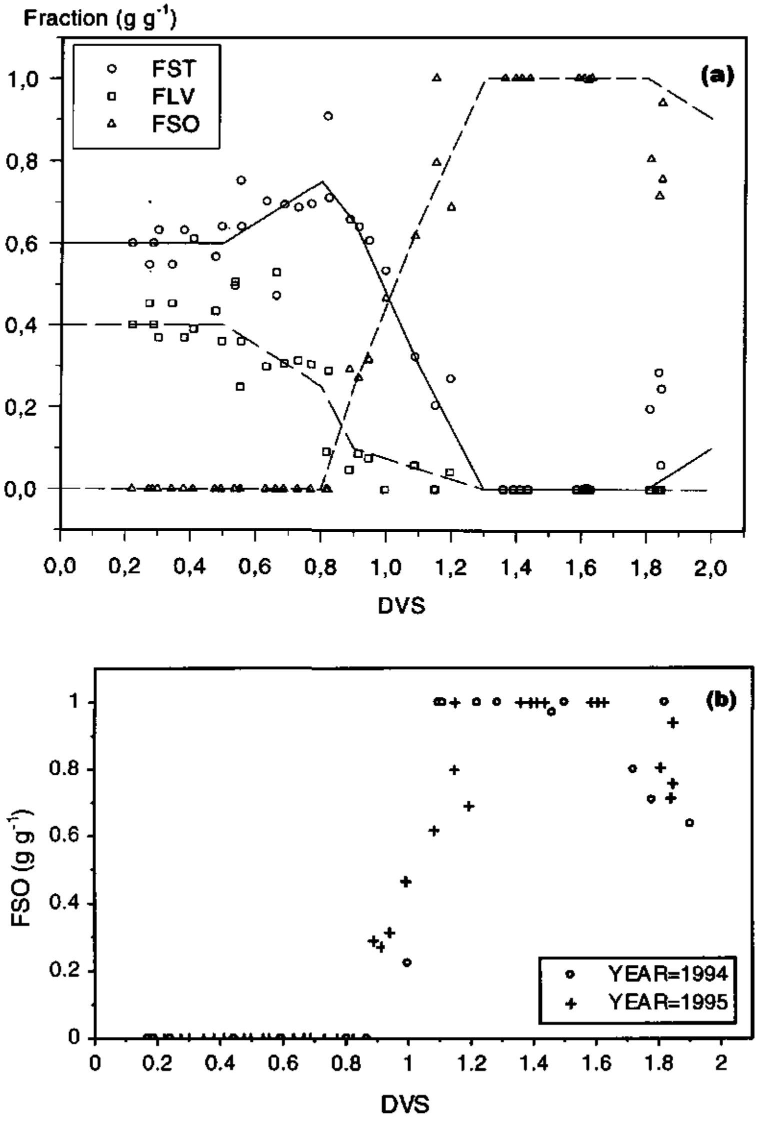

Fig. 4.3. **(a)** Dynamic distribution pattern of dry matter over leaves (FLV), stems (FST) and grains (FSO) in 1995 against development stage (DVS) for cultivars Tebre and L-202.The lines were used in the model. **(b)** Dynamic distribution pattern of fraction to the grains (FSO) against development stage (DVS) during two years (1994 and 1995) for cultivars Tebre and L-202.

• Relative death rate of the leaves (RDR). The dynamics of green and dead leaves is illustrated in Fig. 4.4. The values of RDR are presented in Table 4.2.

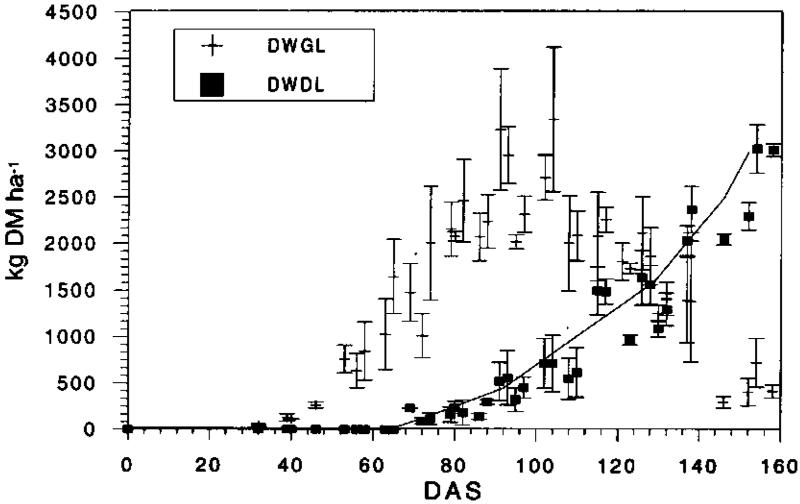

Fig. 4.4. Dynamic dry matter pattern of green (DWGL) and dead leaves (DWDL) in 1995 against days after sowing (DAS) for cultivars Tebre and L-202. Vertical solid lines are standard deviation. The line was used to calculate death rate of leaves as input in the model.

Table 4.2. Calibrated values of Relative Death Rate (RDR, d^{-1}) of leaves for both cultivars Tebre and L-202 in 1995 with development stage (DVS).

DVS	0.0	0.5	0.65	0.9	1.3	1.6	2.0
RDR	0.0	0.0	0.005	0.009	0.01	0.03	0.06

• Mobilization of reserves. The magnitude of the loss of stem weight is presented in Fig. 4.5. The fraction of stem reserves (FSTR) reserved for redistribution later can be calculated by the difference between maximum and minimum stem weight (from flowering onwards) divided by maximum stem weight. An average FSTR of 0.25 for those cultivars is chosen. Redistribution is probably induced when the total demand for sugars exceeds the supply for several days. According to our data mobilization starts at different development stages for Tebre and L-202. A new variable, moment of translocation (MTR) expressed in development stage, is introduced in the model. An average MTR at development stage of 1.3 for Tebre and 1.0 for L-202 is chosen.

• Sink-size related parameters. Spikelet growth factor (SPGF, spikelets g^{-1}) and weight of the grains (WGRMX, mg $grain^{-1}$) present significant differences among cultivars. The average value and standard deviation for SPGF and WGRMX are 42.5±7.1 and 31.1±1.64 for Tebre and 55.5±4.0 and 23.1±0.28 for L-202 respectively. Note, however, that SPGF×WGRMX is similar for both cultivars and equal to 1.3 g of grains dry weight × g^{-1} of above-ground biomass between PI and flowering. Cold-induced sterility was not recorded in any of the years.

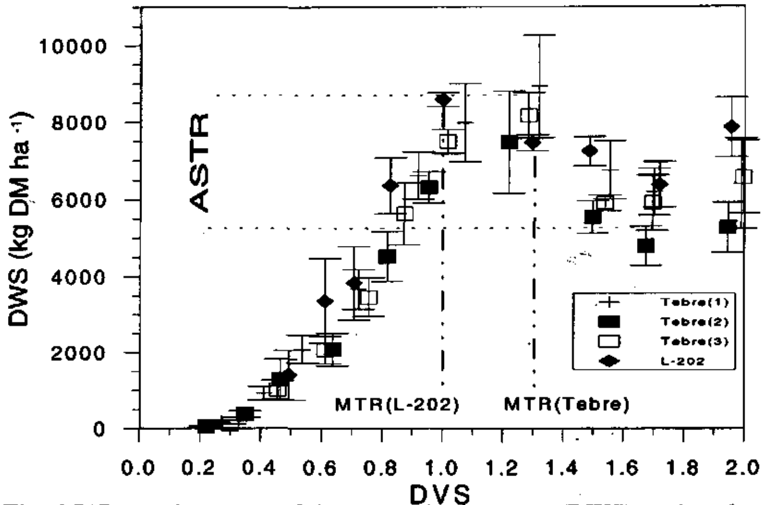

Fig. 4.5. Dynamic pattern of dry matter in the stems (DWS) against development stage (DVS) for cultivars Tebre (number in brackets is farm identification) and L-202 in 1995. ASTR corresponds to the amount of stem reserves that is translocated (FSTR equals ASTR divided by the maximum DWS); MTR correspond to the moment of translocation. Vertical solid lines are standard deviation.

4.3.1.3. Leaf area development

LAI increases as growth advances and reaches a maximum at around heading. Average maximum LAI (measuring only leaf blades) of 6.5 for L-202 and 5.5 for Tebre were reached. After heading, however, LAI declined as the leaves died.

- Relative growth rate of leaf area during exponential growth (RGRL). The exponential phase ends when mutual shading becomes substantial (LAI = 1.0). Figure 4.6 gives a value of 0.009 per degree-day for the RGRL.

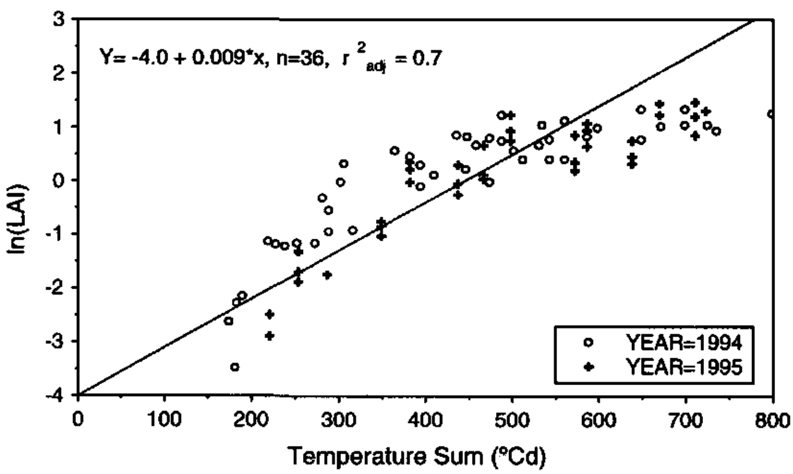

Fig. 4.6. Relation between the natural logarithm of LAI (leaf blade area), for free rowing direct seeded young rice plants, and temperature sum (°Cd, Tbase =10°C) during 1994 and 1995 for cultivars Tebre and L-202. Fitted line for Tsum≤500 °Cd.

• Specific leaf area (SLA). Figure 4.7 shows the specific leaf weight (SLW), inverse of SLA, at various development stages in 1994 and 1995. SLW is plotted instead of SLA because linear equations can be fitted. The scattering of the data, however, is quite large. An average SLA value of 20 m^2 leaf kg^{-1} DM was obtained, slightly lower at flowering and slightly higher at early development stages.

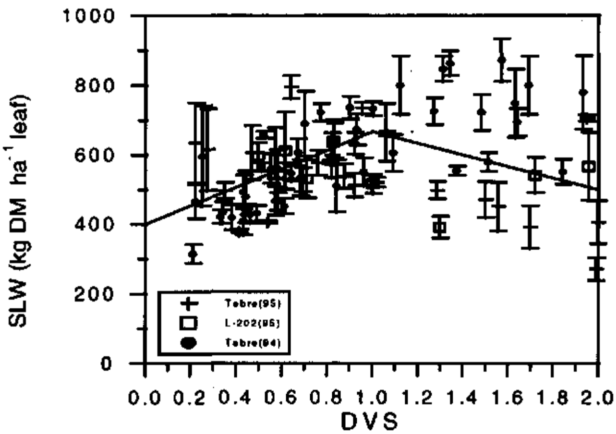

Fig. 4.7. Experimental data (points) and calibrated relation (line) between specific leaf weight (SLW) and development stage (DVS) for cultivars Tebre in 1994 and 1995, and L-202 in 1995. Vertical solid lines are standard deviation. The solid line was used in the model.

• Specific stem green area (SSGA). Figure 4.8 shows the specific stem green weight (SSGW, experimental data and calibrated values), inverse of SSGA, with development stage in 1994 and 1995. SSGW increases until development stage 1.2. Then it diminishes until DVS≅1.5. From development stage 1.5 onwards (until maturity), SSGW has, on average, a slight increase.

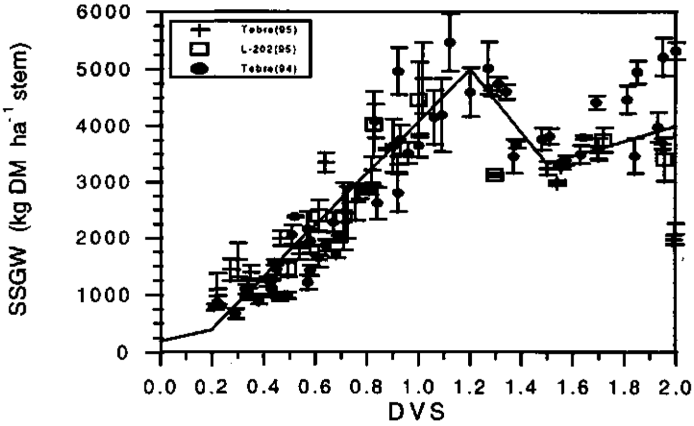

Fig. 4.8. Experimental data and calibrated relation (line) between specific stem green weight (SSGW) and development stage (DVS) for cultivars Tebre in 1994 and 1995, and L-202 in 1995. Vertical solid lines are standard deviation. The solid line was used in the model.

4.3.2. The Validation Procedure

4.3.2.1. Crop development validation

Crop development in this model is considered exclusively temperature dependent. The crop development rates were calibrated with the linear model of Gao et al., (1992). Simulated dates approximated within a range of five days, after or before, the observed ones.

4.3.2.2 Crop growth validation.

No stem green area contribution to leaf area was considered for crop growth simulation because of better overall fit. When adding stem green area, growth rates (i) increased too early at the first (canopy cover limiting) phase and (ii) were too high during the generative (radiation limiting) period. In all subsequent simulation, LAI was defined as leaf blade area without any contribution of leaf sheath or stem area. The ORYZA1 model allows to use either simulated or measured values of LAI for simulating crop growth. Thus, both options are presented in Fig. 4.9 with the comparisons between simulated and observed dry matter values during the growing season in 1995: WTDM (above-ground, not including dead leaves), WSO (grains). The degree of correspondence between the model and the experimental data during the growing season was improved by minimizing the sum of squares of the differences between observed and simulated biomass. Table 4.3 shows that the root mean square error of the prediction is in the order of 5% of final biomass. The results for the runs with LAI simulated were very close to the ones with LAI measured (showing that LAI was simulated properly). Regression between the difference of predicted and observed values versus observed values for above-ground (WTDM) and grains (WSO) biomass show that the intercept was not significantly different from 0 ($p>0.05$) in any case (Table 4.3). The slope was in all cases significantly different from 0 and had positive values between 0.05 and 0.08 indicating the overestimation of the predictions. This shows that the prediction error increases as the crop grows. Figure 4.10 shows measured and simulated values of WTDM and WSO for the validation runs using the data of 1994 and 1996. The root mean square error of above-ground and grains biomass was 2275 and 1304 kg ha^{-1}, respectively (about 10% of final biomass). Incomplete recovery of dead tissues can contribute to discrepancy between simulated and observed above-ground biomass after flowering. The regression between the difference of predicted and observed versus observed values for WTDM and WSO respectively showed that the intercepts were -77.8 ± 496.1 kg ha^{-1} ($p=.87$) and 167 ± 254 kg ha^{-1} ($p=.51$), and the slopes were -0.204 ± 0.047 ($p=.0001$) and -0.107 ± 0.051 ($p=.04$). As in the 1995 dataset, the intercepts were not significantly different from 0 ($p>0.05$), but the slopes of both were. These results show that the prediction was accurate until flowering (Figs. 4.9

and 4.10; DAS ca. 100). From flowering onwards the prediction error increased, and especially in Fig. 4.10. Cultivar L-202 in 1996, in particular, had a significant sink limitation due to insufficient number of spikelets. Spikelet number of L-202 in 1995 and other measured years was approximately 45000-49000, but in 1996 it was only 37000 due to a low plant establishment.

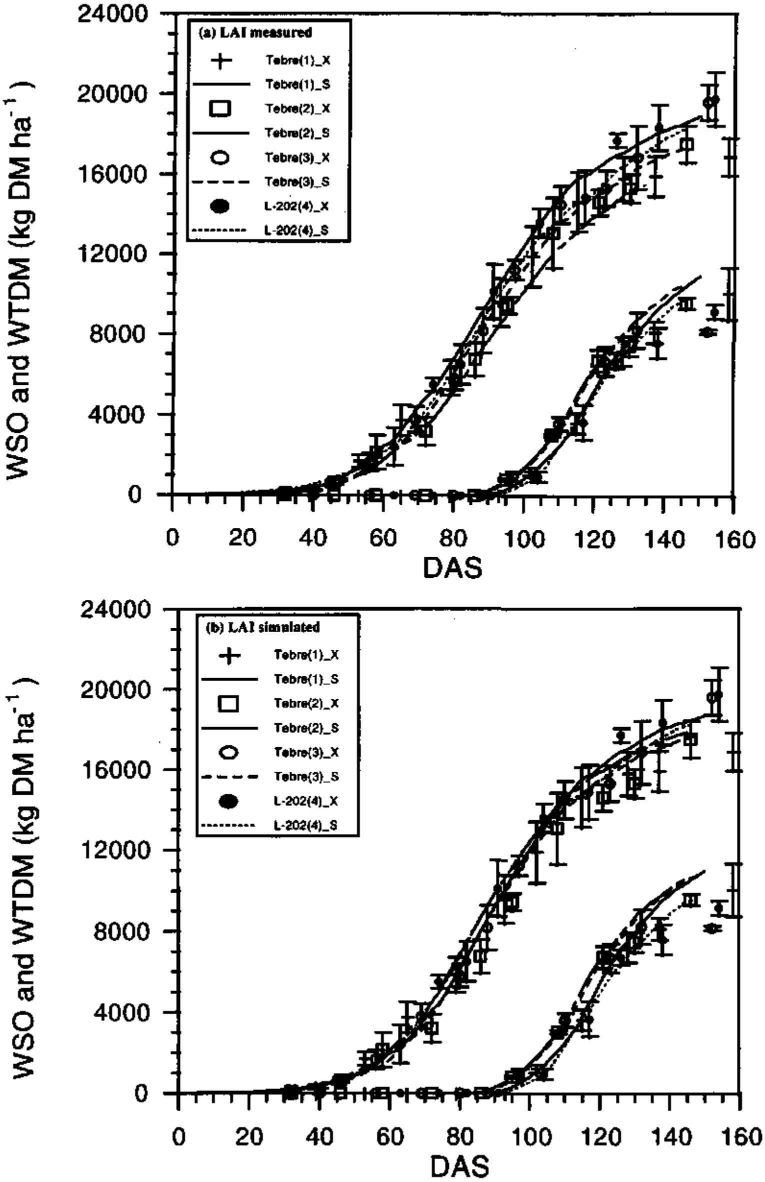

Fig. 4.9. Measured (*_X) and simulated (*_S) weights of above-ground green biomass (WTDM) and grain (WSO) against days after sowing (DAS) for cultivars Tebre and L-202 (number in brackets is farm identification) in 1995 by using the **(a)** measured and the **(b)** simulated LAI time course. Vertical solid lines are standard sampling error.

Table 4.3. Regression analysis between the difference of predicted and observed values versus observed values for above-ground (WTDM) and grains (WSO) biomass with the 1995 dataset by using the measured and the simulated LAI time course. In addition, the root mean square error (RMSE in kg ha^{-1}) of the predictions is given.

N=39	LAI measured		LAI simulated	
	WTDM	WSO	WTDM	WSO
Intercept	-103.5±238.1	-83.6±82.7	-552.6±316.7	-75.0±77.3
(kg ha^{-1})	(p=.66)	(p=.32)	(p=.09)	(p=.34)
Slope	.083±.020	.046±.017	.069±.027	.052±.016
	(p=.0001*)	(p=.012*)	(p=.015*)	(p=.003*)
RMSE (kg ha^{-1})	1242	442	1161	431

* The value is significantly different from 0 at the α=0.05 probability level.

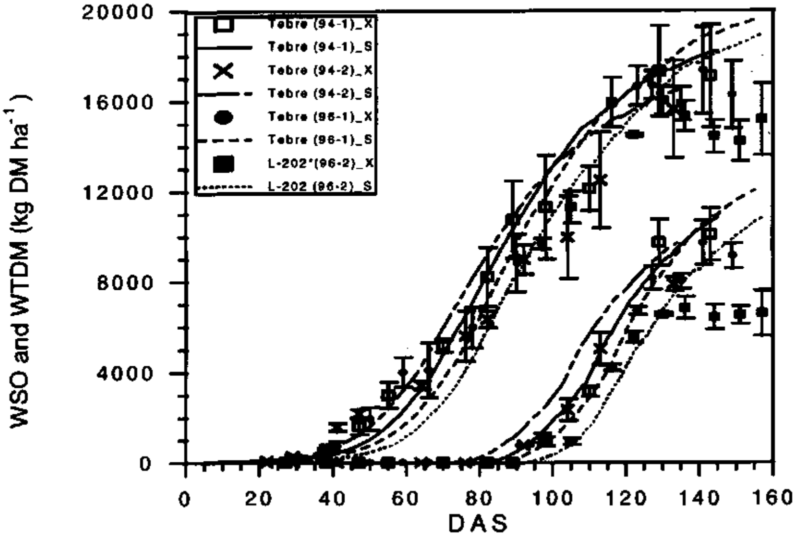

Fig. 4.10. Measured (*_X) and simulated (*_S) weights of above-ground green biomass (WTDM) and grain (WSO) against days after sowing (DAS) for cultivars Tebre and L-202 (number in brackets is year and farm identification) in 1994 and 1996. Vertical solid lines are standard sampling error. *Sink limitation was observed for L-202 in 1996.

4.3.2.3 Leaf area development validation.

The leaf area dynamics are very important for crop growth, especially at the early stages before the canopy closes. The longevity of the green tissue must be considered when assessing the photosynthetic contribution of different plant parts during ripening. The panicle becomes yellow relatively early in ripening but the leaves remain green much longer. Figure 4.11 presents the observed and simulated leaf area during the growing cycle in 1994 and 1995. Standard errors of measurement in LAI, especially high during the ripening phase due to the difficulty in differentiating green healthy from yellow senesced leaves, also contribute to the high prediction error at late stages.

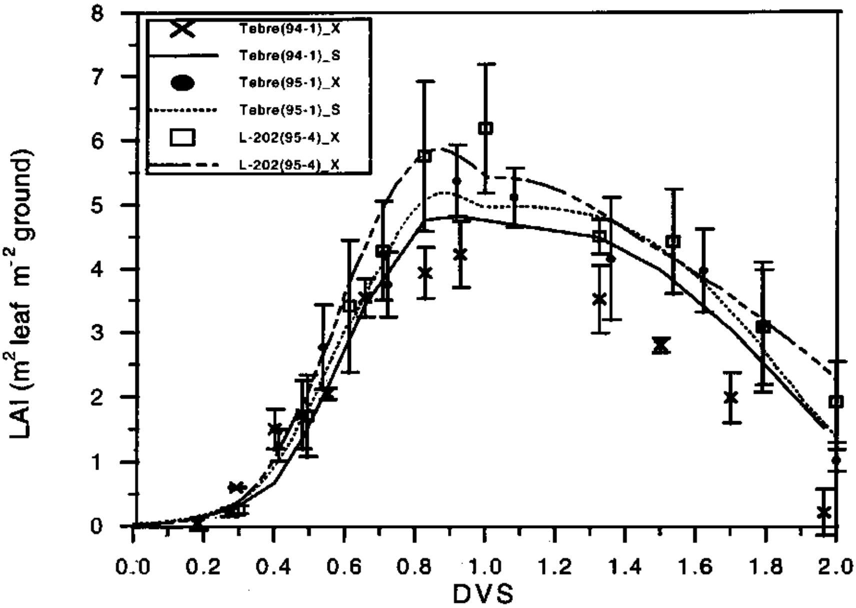

Fig. 4.11. Measured (*_X) and simulated (*_S) LAI (leaf blade area per unit of soil area) against development stage (DVS) for cultivars Tebre and L-202 (number in brackets is year and farm identification) in 1994 and 1995. Vertical solid lines are standard sampling error.

4.4. DISCUSSION

4.4.1. Crop development

To define accurately the main physiological stages is of major importance. Maturity stage, especially, is different from harvesting stage. Harvesting date, though not maturity stage, depends on cultural and farm management. A lot of data is available on harvesting date, but not on maturity. Maturity stage was defined from the growth curves and it usually coincided with a 26-25 percentage moisture content of the grain.

The results obtained in development rates had values with less than three percent variability. L-202 and Tebre have a similar total growth duration, from sowing to maturity. L-202 had, however, a lower pre-heading and a higher post-heading development rate than Tebre. This means that L-202 takes more days to flower and has, thus a higher biomass at flowering, but a shorter post-heading period. This development rate difference has effects; higher maximum LAI, later moment of translocation and higher grain number but smaller individual grain weight (Table 4.4) for L-202 in comparison with Tebre.

Table 4.4. Summary of the calibration for the main rice characteristics in the Ebro Delta (Spain).

Cultivar	Tebre	L-202
Origin	Spain	California (USA)
*Overall development rate $(^{\circ}Cd)^{-1}$	0.606×10^{-3} (similar for both cultivars)	
Develop. rate pre-flowering $(^{\circ}Cd)^{-1}$	1.033×10^{-3}	0.875×10^{-3}
Develop. rate post-flowering $(^{\circ}Cd)^{-1}$	1.500×10^{-3}	1.933×10^{-3}
*Fraction of stems translocated	25%	
Translocation moment (DVS)	1.3	1.0
Spikelet growth factor (spikelets g^{-1})	42.5	55.5
†Panicles per square meter	400-450	600-650
†Grains per square meter	32,000-36,000	44,000-49,000
Weight of 1000 grains (g)	31	23
†LAImax	5.5	6.5
†Harvest Index	0.54	0.45
*Extinction Coefficient	The rice crop at the early stages has more erectophile leaves and with age becomes more planophile; 0.35 during the vegetative stage, 0.49 during the internode elongation stage and 0.61 during the ripening period.	
*Nitrogen dynamic distribution in the leaves	It diminishes with development stage. Optimal values were: 3.5% N at PI, 2.5% N at flowering and 1.3% at maturity.	
*Partitioning of assimilates	A decline in the partitioning to the grains accompanied by an increase in partitioning to the stems at the end of the ripening phase was observed. This feature experienced in both campaigns (1994 and 1995) could have been induced by sink limitation or lodging.	
*Death rate of leaves	It starts at panicle initiation and continues until maturity. Calibration results showed (Table 4.2) and used in this model, are typical for good management and optimal conditions.	
*Growth rate of leaves at the exponential initial phase	A value of 0.009 $^{\circ}Cd^{-1}$ was found for a base temperature of 10 °C	
*Specific leaf area (m^2 leaf kg^{-1} DM)	From 25 (DVS≈0.2) to 15 (DVS≈1)	
*Specific stem green area (m^2 stem kg^{-1} DM)	From 20 (DVS≈0.2) to 2 (DVS≈1.2)	

* No significant differences between cultivars was found.

† Not input in ORYZA1 model.

4.4.2. Crop growth

The growth rate of the rice crop is determined by weather conditions, particularly radiation and temperature. It can be determined from the slope of the curve between total above-ground dry matter and days after seeding. According to our results three clear stages are distinguishable, and this agrees with Hsiao (1993); a first phase (canopy cover limiting), a vegetative and generative period with the highest growth rate (radiation limiting) and a senescence phase where the slope tends to diminish again. At our experimentation sites, a standard growth rate during the intermediate phase of approximately 250 kg dry matter ha^{-1} d^{-1} was achieved. During the grain filling period, grain growth was in the order of 170 kg dry matter ha^{-1} d^{-1}. It seems that from DVS 1.6≈1.7 onwards (after the so-called "rapid grain growth"), the crop growth slowed down, and especially the grains dried until they reached maturity. ORYZA1 v.1.3 seems to overestimate growth rate and therefore grain production at those late stages. This result did not allow changes to a higher value of SLNW at the last stages (see Fig. 4.2b). This error at those late stages may be due to an overestimation of leaf photosynthesis and perhaps to an underestimation of maintenance processes. The finding that simulated growth by the end is larger than actual growth is opposite to what has been recently found in sugarbeet (Duke, 1997), where maintenance processes were overestimated.

The fact that the slopes in the regression analysis between the difference of predicted and observed values versus observed values (Table 4.3) were still significantly different from 0 is an expression of the fact that we did not push the calibration procedure to the extreme. We used measured data as model input and we did not want to change them just to improve the fit. The objective was to test the performance of ORYZA1 and understand plant interrelationships, not to minimize the deviations at any cost.

ORYZA1 v1.3 simulates the development of number of spikelets, as well as grain filling in dependence of temperature and radiation. However, relevant rice literature (Matsuo et al., 1995 and Shin et al., 1994) mentions also a strong relation between spikelet number and management. A correct simulation of the sink size was found a key for understanding the source-sink interrelationships.

Sink limitation could also play a role at those stages. This would reduce photosynthesis or lead to storage in the stem as shown in Fig. 4.3. This effect was clearly visible for cultivar L-202 in 1996 (see Fig. 4.10). It is not a matter only of the grain number but also of the weight/size of the grains. The product of SPGF×WGRMX (number of spikelets per growth between PI and flowering, times the weight of the grains) was similar for both cultivars. This implies that there may be a compensatory relationship between the spikelet number and the grain size so that the two could cancel out each other's variation. This result indicates that under potential production, final yield can be estimated from the growth of above-ground dry matter between panicle initiation and flowering stage. This result is in accordance with Yoshida (1981), who mentioned that yield capacity is determined in the reproductive pre-heading stage. It also addresses the importance of having a sufficiently high LAI at panicle initiation stage for intercepting as much photosynthetically active radiation as possible.

A cold-induced sterility was not recorded, either because of cultivar adaptation or because of proximity to the sea of the study area. In fact, rice in Europe is grown mainly in coastal areas such as the Camargue, Guadalquivir marshes, and the eastern part of the Po valley, besides the Ebro Delta. Minimum recorded night temperatures at flowering stage were 20ºC in 1995 and 1996, and 19ºC in 1994. Temperature, however, is still implied through the effects on development rate, photosynthesis and leaf area extension growth.

4.4.3. Leaf Area Development.

A sensitivity analysis of RGRL showed an enormous variation in LAI just induced by slight variations in RGRL. A proper LAI simulation is as important for determining crop growth as RGRL is for simulating LAI. This strong RGRL sensitivity to the overall crop growth is a weakness that deserves further consideration.

Average specific leaf area (Fig. 4.7), 20 m^2 leaf per kg dry matter (500 kg dry matter per hectare of leaf), was as commonly mentioned in literature. SLA was, however, slightly higher at early stages and lower at flowering.

Average specific stem green area (Fig. 4.8), SSGA, changed strongly with development stage. The ratio of SSGA at flowering to the value at early tillering was in the order of 10:1 (e.g. with SLA the ratio is less than 2:1). This result illustrates the strong thickening of the stems. The best simulation for total above-ground biomass was achieved, however, when neglecting the contribution of stem green area to the photosynthesis. When adding stem green area growth rates increased too early and too high, while without adding it, the simulated rice growth fitted accurately field data.

L-202 had a larger maximum LAI (LAI at flowering) than Tebre (a short-grain cultivar). This effect, as mentioned above, should be understood on the basis of its development rate.

4.4.4. Growth and development extrapolation in the last 10 years

Rice yield variability due to climate variability can be assessed by using the calibrated and validated model. Data on rice yields over the last ten years in the Ebro Delta was obtained from Caballero i Lluch (1992) and the local experimental agricultural station (IRTA). They are average actual yields at field level, far from potential yield. They give, though, a trend on the interannual yield variability. The simulated potential yields during the last ten years were calculated for a standard sowing date such as the 20th April. Figure 4.12 presents those results. Interannual rice variability is small (coefficient of variance of 10%). The trend in simulated potential yields and measured actual yields was similar with a correlation coefficient of 0.7. As in the validation section, the simulated values were always higher than the measured ones.

Additionally simulation results with different sowing dates within one year, show that early seeding in general is positive for final yield. This result is in accordance with normal practice. Farmers in the study area like to sow early, even though it is commonly hampered either by winter rains that do not allow early ploughing or by the control measures of wild rice.

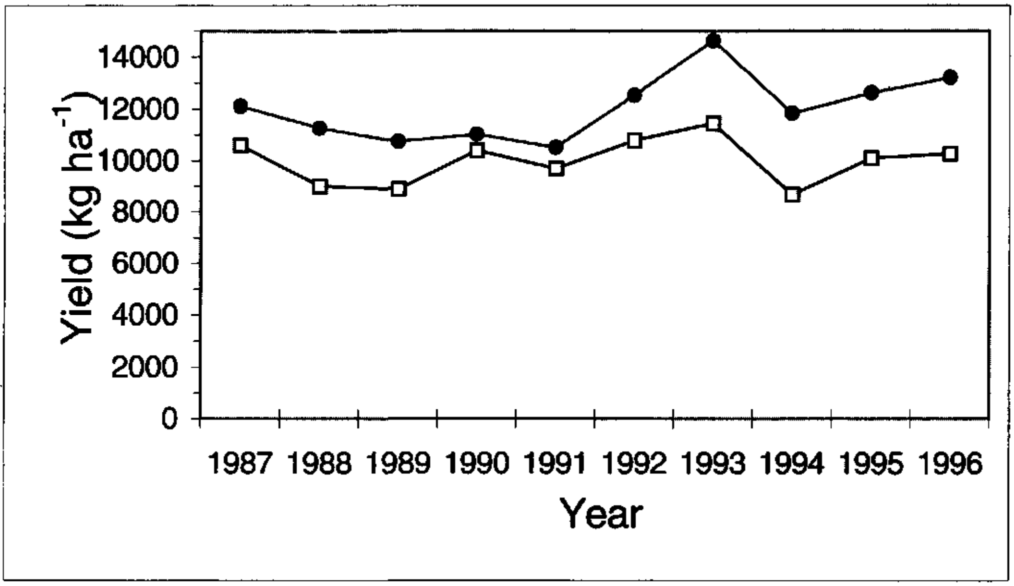

Fig. 4.12. Simulated potential yields (•) and observed actual farmer's yield (□) at 14% moisture for cultivar Tebre in the last ten years at the Ebro Delta.

4.5. CONCLUSIONS

For direct-seeded rice grown in a temperate climate (Ebro Delta, Spain) under optimal conditions (potential yield, limited by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation), the following conclusions can be drawn:

(1) Tebre and L-202 having a similar overall growth duration, but have different development rates in the pre-heading and post-heading period which induce differences in plant properties between cultivars (Table 4.4).

(2) The best simulation for total above-ground biomass was achieved when the contribution of stem green area to the photosynthesis was neglected.

(3) A good simulation of (i) development and (ii) LAI is essential. At present time, LAI simulation during the growing cycle is very sensitive to the RGRL value.

(4) Simulation results show that ORYZA1 can simulate rice growth accurately until flowering. After flowering, however, divergences appear and increase specially after DVS≈1.6-1.7. The main sources of error may be caused by a limited comprehension of the ripening, maintenance and sink limitation processes.

(5) Experimental data of several years (Fig. 4.10) show that during the last stages (DVS>1.6≈1.7) there is little growth. Drying of grains is the main process. This is in accordance with the low stem contribution to photosynthesis.

(6) A compensatory relationship appears between the spikelet number and the grain size canceling each other's variation. This implies that two cultivar-specific characteristics could be joined to form a rather stable variable, namely sink size, independent of cultivar type.

(7) The climatic variability assessment over the last ten years showed a small variation (CV=10%) in rice yield. Simulated and measured rice yields over the last ten years, however, showed a similar trend, in spite of a considerable yield gap between actual and potential yield in all years.

4.6. ACKNOWLEDGMENTS

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Use of remote sensing at field level for monitoring crop status

Abstract:
The present study aims to monitor rice crop status during the growing season by estimating its aboveground biomass and leaf area index (LAI) from field reflectance measurements taken with a hand-held radiometer. First, vegetation indices (RVI, NDVI, WDVI, PVI) were calculated from rice crop reflectance. The fraction of intercepted photosynthetically active radiation (PAR), f_{PAR}, is calculated based on a physical reflectance model from the vegetation indices. WDVI and PVI, indices that correct for soil reflectance, show a more linear and less scattered relation than NDVI and RVI. The NDVI relationship with f_{PAR}, gave a good prediction during the vegetative period but saturated at $f_{PAR} \geq 0.4$. The soil reflectance needed for PVI and WDVI could be easily standardized for continuously flooded fields (10.2% = red reflectance; 7.0% = near-infrared reflectance). Two procedures are discussed: (a) Estimation of leaf area index (LAI) and (b) estimation of biomass. The first links f_{PAR} with LAI by means of the extinction coefficient (K), which varies during the growing season. The dynamic behavior of K is analysed and calibrated for different development stages. LAI of the rice crop was estimated directly from the calculated f_{PAR} once K was established. This procedure accounted for only 67% of the variance in LAI. The second uses the Monteith model that requires one crop specific parameter, the conversion factor (α) for intercepted PAR into dry matter. Values of α for direct-seeded paddy rice were 2.25 g MJ^{-1} for total aboveground biomass over the growing period, but were smaller towards the end. Estimation of biomass from remote sensing data appears to be more reliable than estimation of LAI.

Keywords: Vegetation indices; Crop reflectance; Extinction coefficient; Radiation; Biomass; LAI.

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5.1. INTRODUCTION

The physical fundamentals of the reflection of solar radiation from vegetation canopies are now relatively well understood. Theoretical models have been developed to describe the reflectance from single leaves to complete crop canopies (Goudriaan, 1977; Baret et al., 1989). Bunnik (1984) demonstrated that reflection of red, green, and near-infrared radiation contains considerable information about crop biomass owing to the contrast between soil and vegetation. During the past several years, estimates of biomass, ground cover and leaf area indexes (LAI) as a function of spectral reflectance measurements have shown promising results (Bouman et al., 1992; Leblon et al., 1991; Clevers, 1989). However, paddy rice being grown in continuously flooded fields, is a special crop which deserves particular consideration, as the layer of water on the soil surface modifies the spectral reflectance of the soil-plant system (Gilabert and Melià, 1990; Patel et al., 1985).

A remote-sensing model relating reflectance data to rice parameters would be useful for monitoring and yield prediction because:

(i) It allows fast, non-destructive and relatively cheap characterization of crop status (Bouman, 1995),
(ii) It can be used to initialize crop parameters appearing in rice growth simulation models, (e.g. Ten Berge et al., 1994), and
(iii) It can be extended to regional level (Ishiguro et al., 1993).

The rice plant usually takes 3 to 6 months from germination to maturity, depending on the cultivar and the environment in which it is grown. Rice in the Ebro Delta (Spain) takes almost 5 months (140 days) to reach maturity (Casanova, 1993). Agronomically, it is convenient to regard the life history of rice in three growth stages: vegetative, reproductive pre-heading, and reproductive post-heading. The vegetative stage refers to a period from germination to the initiation of panicle primordia; the pre-heading period from panicle primordia initiation to heading; and the post-heading period from heading to maturity (Yoshida, 1981).

In this paper, the aim is to relate reflectance measurements taken with a hand-held radiometer to rice parameters. Christensen and Goudriaan (1993) showed a relation between the fraction of intercepted photosynthetically active radiation (PAR), f_{PAR}, and spectral measurements. Thus, f_{PAR} can be easily calculated from spectral reflectance and is considered a key ecophysiological parameter for estimating crop status.

Two main approaches are discussed: (a) the estimation of leaf area index (LAI) and (b) the estimation of aboveground biomass. The estimation of LAI from f_{PAR} is derived from Beer's Law (Monsi and Saeki, 1953). However, the dynamics of the extinction coefficient (K) during the growing season need to be analysed and calibrated for rice cultivars. Once the K is calibrated, LAI estimates are easily made. Option (b), based on a simplified model, assumes that crop production results from photosynthesis and is proportional to the intercepted photosynthetically active radiation (400-700 nm) accumulated during the growing season. This model requires two crop specific parameters, the conversion factor for intercepted PAR into dry matter and a harvest index for converting total biomass to grain yield (Monteith, 1973).

5.2. MATERIALS AND METHODS

5.2.1. Description of field measurements

Crop leaves intercept incident solar radiation. Their area is commonly described as leaf area index (LAI) defined as the sum of area of all leaves divided by the ground area above which the leaves have been collected (Yoshida, 1981). LAI was determined here by measuring leaf blade area with a LI-300 Area Meter.

The trials were performed at four farms in the Ebro Delta, Spain, during the rice-growing seasons of 1994 and 1995. The experimental fields included a wide range of environmental conditions, but without water, nutrient, weed, disease or pest limitations. The rice cultivars were Tebre and L-202. The topsoil texture ranged from loam to silty clay loam. Reflection measurements and crop samples were taken at three sites within the parcels on an approximately biweekly basis during the rice growing season. A frame of 0.5 m^2 was used for crop sampling.

Reflection measurements were taken with a hand-held MultiSpectral Radiometer (MSR) (CROPSCAN Inc., 1993). A total of 8 bands were measured in the field of which two were used for modelling:

(i) band 5, red, central band-width = 660.9 nm;

(ii) band 8, near-infrared, central band-width = 813.2 nm.

The CROPSCAN was attached to a Data Logger Controller (DLC) for input and storage of data. Calibration of each wavelength was not considered necessary and was made on a lambertian surface (white reference plate). Incident radiation was measured with a view-angles of 180°, and that reflected by the crop with view-angles between 25° and 30°. Canopy reflectance was computed as the percentage of incident radiation reflected upward.

The Decagon Sunfleck Ceptometer (Model SF-80, Decagon Devices, Inc. 1989) was used to measure the photosynthetically active radiation (400-700 nm) above and below the canopy. The instrument has 80 light sensors placed at 1 cm intervals along a probe. A microprocessor scans the 80 sensors and computes an average reading on command. Daily totals of global short-wave radiation were measured at an agricultural experiment station situated in the Ebro Delta, (Amposta).

5.2.2. Vegetation Indices (VIs)

Vegetation indices are computed as a carefully chosen combination of reflection coefficients in various wavebands. The main function of vegetation indices (VIs) is to minimize the effect of disturbing factors on the relationship between reflectance and crop characteristics of interest such as crop type, LAI, or canopy biomass (Bouman, 1995). Undesirable disturbing factors are, for example, differences in soil background or atmospheric conditions (Clevers et al., 1991). The first index to be used was the IR/R ratio (Rouse et al., 1973). The same authors used a normalized difference vegetation index (NDVI) for estimating crop characteristics. To find an index independent of soil influence, Wiegand and Richardson (1987) introduced the perpendicular vegetation index (PVI) for which the reflectance of the soil has to be known. RVI, NDVI, PVI and WDVI (Clevers, 1989) were used in the present study. The corresponding Eqs. are as follows:

$$RVI = \frac{\rho_{ir}}{\rho_r} \qquad \text{(Eq. 5.1)}$$

$$NDVI = \frac{(\rho_{ir} - \rho_r)}{(\rho_{ir} + \rho_r)} \qquad \text{(Eq. 5.2)}$$

$$PVI = \sqrt{[(\rho_{ir} - \rho_{ir,s})^2 + (\rho_r - \rho_{r,s})^2]} \qquad \text{(Eq. 5.3)}$$

$$WDVI = \rho_{ir} - \left(\frac{\rho_{ir,s}}{\rho_{r,s}}\right)\rho_r \qquad \text{(Eq. 5.4)}$$

where:

ρ_r = red reflectance;

ρ_{ir} = near infrared reflectance;

$\rho_{r,s}$ = red reflectance of bare soil;

$\rho_{ir,s}$ = near infrared reflectance of bare soil.

5.2.3. Deriving fraction intercepted radiation from spectral reflectance

The ratio between transmitted and incoming photosynthetically active radiation (PAR; 400-700 nm) under a canopy decreases approximately exponentially with leaf area index (LAI), so that the fraction of PAR intercepted can be written:

$$f_{PAR} = 1 - e^{-K*LAI} \qquad \text{(Eq. 5.5)}$$

where:

f_{PAR} = fraction of PAR intercepted by the canopy (for all practical purposes identical to the proportion of ground covered by the crop);

K = extinction coefficient.

The ratio ρ of radiation reflected from the canopy to the incoming radiation is influenced by the reflectance from both canopy and soil. The spectral reflectance to red (ρ_r) and near infrared (ρ_{ir}) radiation from a crop (Goudriaan and Van Laar, 1994) is given by

$$\rho_r = \frac{\rho_{r,\infty} + (\eta_r / \rho_{r,\infty}) \exp(-2K_r LAI)}{1 + \eta_r \exp(-2K_r LAI)} \qquad \text{(Eq. 5.6)}$$

where

$$\eta_r = \frac{\rho_{r,\infty} - \rho_{r,s}}{\rho_{r,s} - 1/\rho_{r,\infty}} \qquad \text{(Eq. 5.7)}$$

and similarly

$$\rho_{ir} = \frac{\rho_{ir,\infty} + (\eta_i / \rho_{ir,\infty}) \exp(-2K_i LAI)}{1 + \eta_i \exp(-2K_i LAI)} \qquad \text{(Eq. 5.8)}$$

where

$$\eta_i = \frac{\rho_{ir,\infty} - \rho_{ir,s}}{\rho_{ir,s} - 1/\rho_{ir,\infty}} \qquad \text{(Eq. 5.9)}$$

$\rho_{r,\infty}$ = red reflectance at infinite LAI;

$\rho_{ir,\infty}$ = near infrared reflectance at infinite LAI.

The parameters K_r and K_i are the extinction coefficients of red and infrared radiation, (K_i=0.5×K_r, Rodskjer 1972). The vegetation indices and f_{PAR} can be considered as parametric expressions in LAI. To obtain the relations between the VI's and f_{PAR}, they must be plotted against each other. The relation between f_{PAR} and the VI's depends on the values of $\rho_{r,\infty}$, $\rho_{ir,\infty}$, $\rho_{r,s}$ $\rho_{ir,s}$. The reflection and extinction coefficients vary significantly among cultivars and species that differ in canopy structure, pigment density, nitrogen content, and structure of the leaves (Wiegand and Richardson, 1987).

5.2.4. Deriving LAI from f_{PAR}

LAI values can be obtained directly from f_{PAR} using Eq. (5.5). However the value of the extinction coefficient *(K)*, which is crop and development stage specific, is necessary. *K* values for a given crop can be extracted from the slope of the linearized version of Eq. (5.5), viz:

$$\ln f_{trans} = \ln (1- f_{PAR}) = -K \times \text{LAI} \qquad \text{(Eq. 5.10)}$$

where f_{trans} is the fraction of radiation that is transmitted through the canopy.

5.2.5. Deriving biomass from f_{PAR}

The amount of dry matter is a time-integrated product of the fraction of intercepted PAR and the daily incident radiation of PAR above the canopy:

$$W_{DM} = \int \alpha \, f_{PAR} \, S_{0,PAR} \, dt \qquad \text{(Eq. 5.11)}$$

where:

W_{DM} = amount of dry matter (g m^{-2});
α = conversion factor for intercepted PAR into dry matter (g MJ^{-1});
$S_{0,PAR}$ = daily incident radiation of PAR above the canopy (MJ m^{-2} d^{-1}) (ca. 0.48 of incoming radiation);
t = time (d).

The f_{PAR} values are derived from the vegetation indices by means of their parametric expressions. The conversion factor for intercepted PAR into dry matter (α) can be moved outside the integration sign if constant during the growing season. Russell et al. (1989) summarized values of α for different species and environmental conditions. Grain yield is a component of total dry matter production. Hence to predict rice production, the final biomass should be multiplied by the harvest index (Horie et al., 1992).

5.3. RESULTS

Rice development progresses (Van Keulen and Seligman, 1987) through three clearly different stages; seeding (DVS=0), flowering (DVS=1) and maturity (DVS=2). Intermediate stages are defined according to a linear model based on temperature (Gao et al., 1992). For Japonica cultivars, the base temperature is 10°C, the optimum temperature 28°C, and the maximum 40°C. The temporal evolution of red and near infrared reflectance in relation to development is presented in Fig. 5.1. The rice crop was continuously flooded during the growing season, except for the last 15 days as in commercial practice.

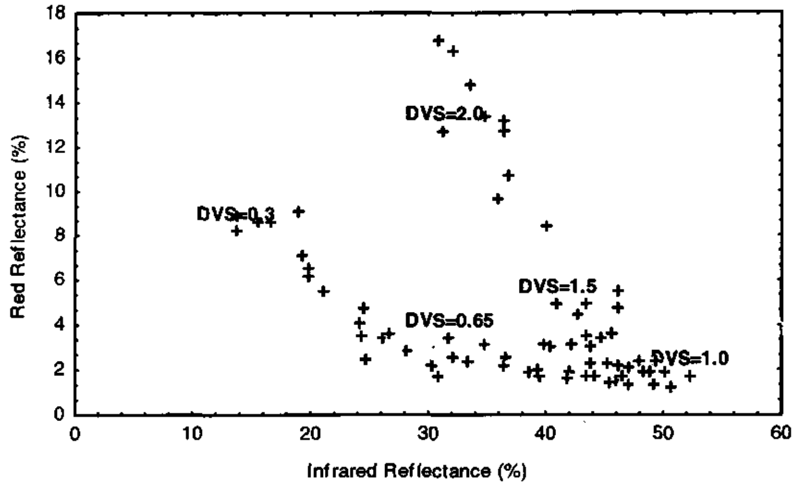

Fig. 5.1. Red and near-infrared reflectance of flooded rice fields during the growing season.

5.3.1. Deriving fraction intercepted radiation (f_{PAR}) from spectral reflectance

The fraction intercepted photosynthetically active radiation (f_{PAR}) was calculated using the Ceptometer data. The experimental data of both years are plotted in Fig. 5.2 using a different symbol for each year and development stage. The f_{PAR} tends to saturate at 94% absorption after flowering.

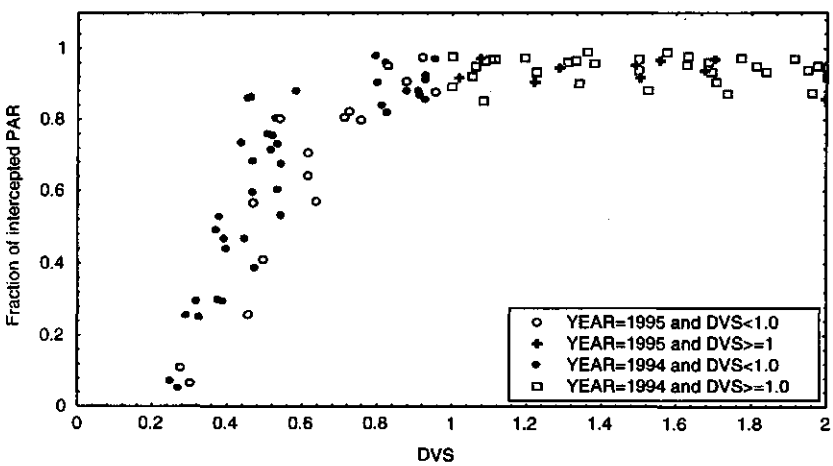

Fig. 5.2. The progress of f_{PAR} with crop development stage (DVS).

Rice is grown on soils of widely varying texture, but most such soils are fine loam to fine clay in their surface horizon (Moorman and Van Breemen, 1978). In coastal areas, however, they may range from loamy sand to silty clay (Casanova, 1993). Soil management practices for direct seeding include harrowing, bulldozing and precision leveling of the soil surface. Therefore, the soil tends to be finely smoothed and crushed. Reflectances measured over various dry and flooded soils with several depths of surface water were examined by an analysis of variance. Soil texture did not significantly affect reflectance (data not shown). The reflectances for dry soil were significantly greater than flooded soil (Table 5.1). For flooded soils (10-20 cm or 5-10 cm depth of surface water), however, reflectance was significantly different for the infrared but not for the red wavelengths. The reflectance values of Table 5.1 were used to calculate the soil reflectance parameter values needed for WDVI and PVI. Averages of 9 measurements were used to calculate each value presented in Table 5.2. In the data, flooded fields were covered with more than 10 cm of surface water.

Table 5.1. Reflectance (%) of bare soil with and without surface water.

Water-Reflectance Effect	Near- Infrared	Red
Bare soil	24.17	21.90
5-10 cm depth of surface water	11.07	10.77
10-20 cm depth of surface water	7.00	10.20
L.S.D. = 0.74		

Table 5.2. Parameter values for Eqs. 5.3, 5.4, 5.6, 5.7, 5.8 and 5.9 estimated from a maximum and a minimum rice canopy in a flooded soil.

	Near-Infrared	Red
Reflectance at maximum LAI	$\rho_{ir,\infty} = 0.477$	$\rho_{r,\infty} = 0.014$
Reflectance from flooded soil	$\rho_{ir,s} = 0.070$	$\rho_{r,s} = 0.102$

Experimental values for the various vegetation indices were calculated for all plots using the Cropscan data. VI's and f_{PAR} can be considered parametric functions of LAI. Thus, rice reflectance and LAI are related by introducing the parameter values from Table 5.2 into Eqs. (5.6) and (5.9). f_{PAR} and LAI are related by Eq. (5.5). Figure 5.3 illustrates the experimental data of 1995 and the fitted physical reflectance models. Figure 5.3 demonstrates that the theoretical curves give a good description of the experimental data. Table 5.3 presents the calibration results between the physical reflectance models and the experimental data. In general, all models fit better in the vegetative and pre-heading stage than in the post-heading stage. The NDVI and RVI models fit well during the vegetative stage. However, they do not give a good prediction after flowering and are highly non-linear. Additionally, NDVI saturates at $f_{PAR} \geq 40\%$. WDVI and PVI, that take into account the soil reflectance, are more linear and have less scatter. However, all tend to overestimate f_{PAR} at the early stage. The WDVI is preferred in all subsequent modelling because of its linearity with f_{PAR}, better overall fit and simplicity. The sensitivity of this model to the parameters $\rho_{ir,s}$ and $\rho_{r,s}$ was investigated because we suspected that the changing depth of surface water had a significant effect on the measured WDVI. However, f_{PAR} values calculated with the lowest and the highest measured reflectances differ only slightly.

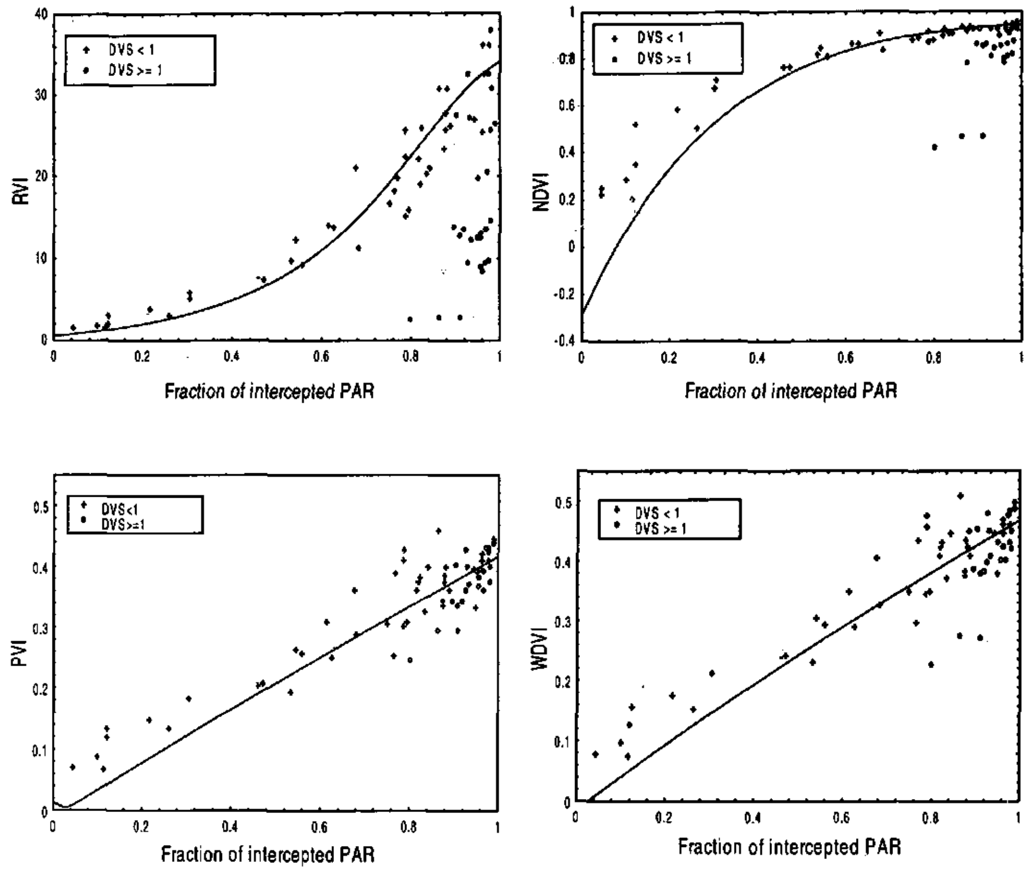

Fig. 5.3. Measured data and theoretical relations between f_{PAR} and the VI's in 1995 at various development stages (DVS).

Table 5.3. Accuracy of estimated f_{PAR} for various VI's and development stages of rice.

		MODEL			
Development stage	N	RVI	NDVI	WDVI	PVI
0<DVS≤1	49	0.102[a]	0.102	0.105	0.105
1<DVS≤2	46	0.437	0.438	0.289	0.248
0<DVS≤2	95	0.264	0.265	0.194	0.174

[a] Values are root mean square error of f_{PAR}.

5.3.2. Estimating LAI

The LAI is plotted against the natural logarithm of the light transmitted using the experimental data from 1995 (Fig. 5.4). According to Eq. (5.10), the negative slope of this relation corresponds to the extinction coefficient (*K*). The spread in the data is greatest in the last development phase. This probably occurs because at the end of the ripening phase, yellow (senesced) plant material was present in most experiments, the canopies were lodged to some degree, and some fields were no longer flooded. A linear model, assuming a constant *K*, would give an extinction coefficient of 0.54. Figure 5.4, however, shows that the extinction coefficient is not constant and increases with development stage. To be consistent with Eq. (5.5), the extinction coefficient is calculated with linear models through the origin (0,0). The calibration of the extinction coefficient, differentiating the three clearly defined development stages, is illustrated in Fig. 5.4. Based on those three discrete values of *K*, LAI can be estimated from f_{PAR} using Eq. (5.10). Estimated LAI is compared with measured LAI in Fig. 5.5. Standard errors of measurement in LAI, especially high during the ripening phase due to the difficulty in differentiating green healthy from yellow senesced leaves, also contribute to a low correlation. The intercept is significantly different from 0 (p=0.001) and the slope is significantly different from 1 (p=0.001).

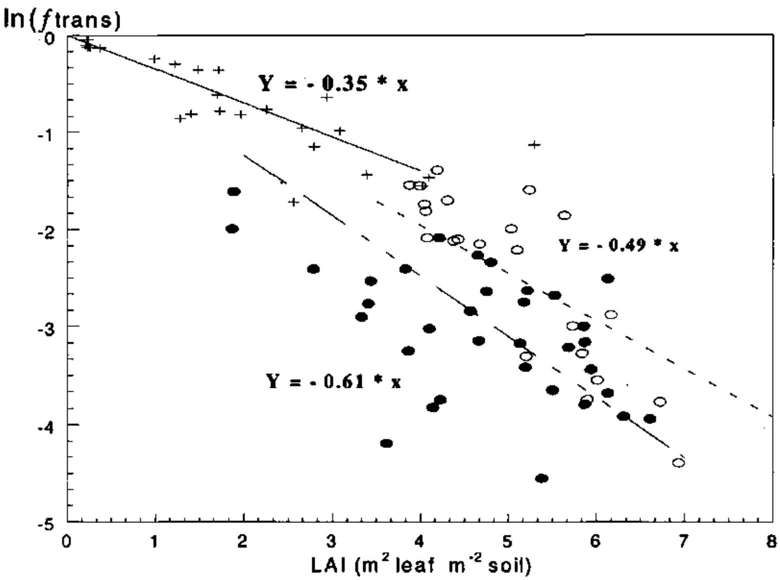

Fig. 5.4. Relationship between the natural logarithm of the fraction of the transmitted light and leaf area index in the 1995 dataset. The line represents the fitted models during the three different development stages. DVS≤0.65, f_{PAR}= $e^{(-0.35\times LAI)}$, r^2_{adj}=0.70, n=25; 0.65<DVS≤1.0, f_{PAR}= $e^{(-0.49\times LAI)}$, r^2_{adj} = 0.72, n=24; 1.0<DVS≤2.0, f_{PAR}= $e^{(-0.61\times LAI)}$, r^2_{adj} =0.27, n=34.

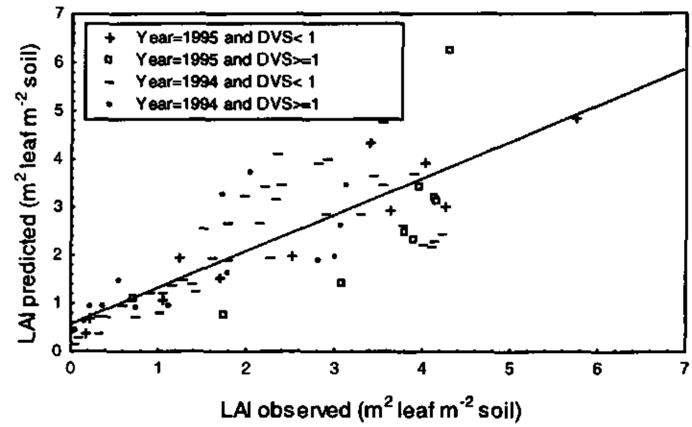

Fig. 5.5. Comparison of observed and predicted LAI from the WDVI-f_{PAR} model. The line represents the fitted linear model: $LAI_{pre} = 0.56 + (0.756 \times LAI_{obs})$, r^2_{adj}=0.67, n=86.

5.3.3. Estimating biomass

f_{PAR} values are derived from the measured vegetation indices and daily f_{PAR} was calculated by linear interpolation for all fields of 1994 and 1995. The daily intercepted PAR of each plot was then calculated as

$$D_{PAR} = f_{PAR} \times S_{o,PAR} \qquad \text{(Eq. 5.12)}$$

where $S_{o,PAR}$ is the daily incoming PAR estimated as 0.48×So, the daily incoming short-wave radiation (300-2800 nm) obtained at the local meteorological station. The accumulated intercepted PAR was then

$$AI_{PAR} = \sum D_{PAR} \qquad \text{(Eq. 5.13)}$$

The measured variable for rice biomass was the total aboveground dry matter (WA). Figure 5.6 shows the results of sequential sampling of aboveground dry matter plotted against AI_{PAR} values estimated from spectral measurements. A strong linear relationship holds during the rice growing cycle explaining 98% of the variance and providing a conversion factor for intercepted PAR into dry matter (α) of 2.25 g MJ^{-1} There is some evidence that α decreases slightly at the late ripening stage.

5.4. DISCUSSION

Temporal analysis of rice crop reflectance indicates variation in biomass and greenness. Near infrared reflectance varies according to biomass, increasing from a

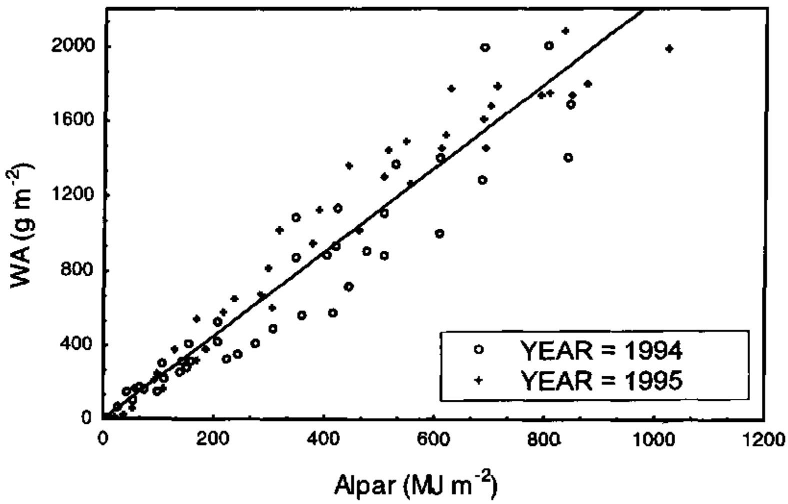

Fig. 5.6. Relationship between measured total aboveground biomass (WA) and estimated accumulated intercepted PAR (AI_{PAR}) during 1994 and 1995 seasons. The line represents the fitted linear model through the origin: $WA = 2.25 \times AI_{PAR}$, $r^2_{adj} = 0.97$, n=102.

minimum of 15% at early tillering to a maximum of 50% at heading. Then it diminishes, corresponding to the decrease in biomass due to death and loss of leaves, to a final value of approximately 33%. Red reflectance can be considered inversely proportional to the greenness of the rice crop. It diminishes from 10% at emergence to 2% at flowering and then increases to 16-18% at maturity due to loss in green brightness by the leaves and stems plus the yellowness of the rice grains.

During the rice growing season, f_{PAR} increased from 0 (at seeding) to a maximum at flowering stage LAI_{max}. During the post-heading period f_{PAR} is assumed constant (ca. 94%). The increase in f_{PAR} is well described from spectral data by physical models. All the models fit better in the vegetative and pre-heading stage than post-heading. The temporal signature of NDVI and RVI change enormously after flowering, probably a result of the developing panicle on the top of the canopy. Furthermore, NDVI tends to saturate very easily ($f_{PAR} > 40\%$). The WDVI and PVI, correcting for soil interference, are almost linearly related to f_{PAR}, and with a minimum difference between before and after flowering. The latter indices, however, need the additional data of reflectance of bare soil. The advantage with paddy rice is that the reflectance of flooded fields can be used in place of bare soil (e.g. $\rho_{r,s}$= 10.2% and $\rho_{ir,s}$= 7.0%). The reflectance for a sandy or clayey soil is similar under a layer of 15 cm of water. Additionally, the model (WDVI-f_{PAR}) is not very sensitive to changes in depth of the surface water. Considering the total data set, the WDVI model seems most appropriate to estimate f_{PAR}.

The estimation of LAI from f_{PAR} requires calibration of the extinction coefficient (K) which is crop and development-stage specific. For rice, K is found to increase with development stage as more erectophile leaves (K=0.35) at the vegetative stage become more planophile (K=0.47) during the pre-heading period and (K=0.62) the post-heading period. Direct estimates of LAI from f_{PAR} and indirectly from spectral reflectance were not very accurate, explaining 67% of the variance in LAI.

Biomass can be calculated directly from f_{PAR} if incident radiation data are available. Biomass relates to accumulated intercepted PAR by the radiation-use efficiency (α); the slope of the line in Fig. 5.6. This figure illustrates that α, though diminishing at the final stages can be considered constant. A value of 2.25 g MJ^{-1} explains up to 97% of the variance in biomass. Biomass during the rice-growing cycle is more precisely estimated than LAI. The mean value of α for rice is similar to values reported for other crops (Russell et al., 1989; Christensen and Goudriaan, 1993). The reduction in radiation-use efficiency of the rice crop at late stages (DVS ca. 1.5), also reported by Horie et al. (1992), is probably an intrinsic phenomenon, as no low temperatures, diseases or pests occurred during this period. This period coincides with the milky dough stage when the death rate of leaves increases. Additional insight and knowledge on rice growth is necessary for understanding the process.

5.5. CONCLUSIONS

Rice has distinct spectral signatures to other crops, but the following conclusions can be drawn:

(1) Physical models relating crop reflectance by means of vegetation indices to the fraction of intercepted photosynthetically active radiation (PAR), f_{PAR}, describe well their time course during crop growth. The NDVI and RVI signature changes greatly from before to after flowering. Additionally, NDVI saturates quickly (f_{PAR}> 40%). However, those indices describe accurately the time course of f_{PAR} during the vegetative stage. WDVI and PVI, independent of soil influence, show a more linear and less differentiated relation before and after flowering. WDVI and PVI are less sensitive to the effect of panicle development and provide the best estimation of f_{PAR} at any time of the growing season. Furthermore, standard reflectance values can be applied to different soil types when continuously flooded ($\rho_{r,s}/\rho_{ir,s}$: 7.0/10.2= 0.686).

(2) The extinction coefficient (K) increases with development stage. At the early stages the crop has more erectophile leaves which become more planophile with

age; K=0.35 during the vegetative stage, K=0.47 during the reproductive pre-heading period and K=0.62 during the reproductive post-heading period.

(3) It is possible to estimate LAI directly from spectral data and the extinction coefficient (K). However, precision is limited (r^2_{adj} = 0.67).

(4) Estimates of biomass are attainable by the energy-based approach, proposed by Monteith (1973). The conversion coefficient for intercepted PAR into total aboveground dry matter, α, diminished slightly at the late stages of development, but an effectively constant value of 2.25 g/MJ can be applied from seeding to maturity.

(5) Biomass can be predicted (r^2_{adj} = 0.97) from spectral reflectance with higher accuracy than LAI.

Field-based predictions have practical applications. Therefore, it is necessary to validate the physical relationships reported here, for different scales of observation and locations.

Yield-gap analysis between rice growth and soil properties

Abstract:
The most important soil properties for rice growth under fully irrigated direct-seeded conditions in the Ebro Delta (Spain), under a temperate Mediterranean climate, were: (i) topsoil CEC, clay and silt content. CEC and clay content of the topsoil had the highest correlation with yield; (ii) pH in the range of 6.9 to 7.9; (iii) Soil salinity, which was negatively related with yield. Soil salinity was highly correlated with the electrical conductivity of the groundwater. The groundwater was found to be of marine origin, and with high differences in its electrical conductivity (from 2 to 60 dS m^{-1}). High groundwater tables did not have significant effects on rice yield, except when the water had a high salt content. Thus, groundwater control would be necessary only if highly saline. Several statistical and mathematical procedures were applied to compare differences in rice yield among parcels. The simple correlation coefficient was useful to determine a pointwise comparison between yields and soil variables. Stepwise regression allowed prediction of yields from soil variables. The law of the minimum of the limiting factors ("Min-Max" method) identified the yield-gap (ca. 3000 kg ha^{-1}) to be due to soil properties. An average yield gap of 1000 kg ha^{-1} remained non-identified due to other factors. These statistical procedures do, however, not provide mechanistic explanations for the plant-soil processes. Several other factors could also have positive effects, even though they did not emerge here. The effects of water limitation in rainfed agriculture under Mediterranean conditions are absent. Yield data for a particular year can be representative for other years under flooding conditions. Thus, results obtained for 1995 can be used to suggest certain types of management in certain areas allowing a relatively high efficiency of natural resource-use also in years for which no statistical analyses were made.

Keywords: Soil salinity; Drainage; Groundwater; Operational model; Clay; CEC.

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6.1. INTRODUCTION

Rice is cultivated throughout the world in many different ways and degrees of intensification. Main cropping differences exist between upland rice and lowland rice. Lowland rice may be irrigated or rainfed. Under fully irrigated conditions, rice may be transplanted or directly seeded. Direct seeding under irrigation is the most common form in Europe, Australia and USA (Hill et al., 1991). Rice cultivation in the Ebro Delta (north-east Spain) occupies an average area of 21000 ha with an average yield of 6500 kg ha^{-1} (MAPA, 1995). In this paper, the aim is to assess the effect of soil properties on rice growth by developing an operational model with predictive capabilities, allowing identification of the yield gap between potential and actual production at farm level.

The potential yield of a rice crop is determined only by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation. Under optimum growth conditions, light, temperature and varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day (e.g. Kropff et al., 1994). Under growth limiting conditions, soil properties have an effect on crop growth (e.g. Patrick et al., 1985; De Datta, 1981; Stein et al., 1997).

A total of 50 fields spread along the Ebro Delta were selected (see Fig. 6.1). Rice growth was monitored and soil properties were measured. In agricultural sciences, research is usually done by selecting one field with different subplots where all the variables except one are similar. The response of the crop to this dissimilar variable is measured and quantified in a straightforward manner (Gomez and Gomez, 1984). This paper tackles the problem in a rather different way by observing directly what is happening in the field. Such an approach is often followed by sociologists, biologists, epidemiologists, etc. It exploits and analyses the available environmental variability and its effects (Webster and Oliver, 1990), instead of explicit experimentation. By no means we believe this methodology to be the best one; it is just considered to be an alternative approach.

For identifying and quantifying the main soil properties that limit rice production two methodologies are discussed:

(i) Multiple linear regression.

(ii) The law of the minimum of the limiting factors ("Min-Max method"), first proposed by Von Liebig (1855).

As part of this study, special emphasis was given to assessing drainage status and soil salinity; the poor drainage conditions and high salinity of some of the soils in the study area was expected to have a major influence on rice growth.

This operational model, even though specific for the Ebro Delta, is intended to have a strong predictive capability at farm level. It is a rule-based model that allows identification and quantification of the differences between the actual and potential production. It will allow identification of the main soil properties responsible for the yield gap. In addition, it will help to understand better the behaviour of submerged soils in relation to the rice plant.

6.2. MATERIALS AND METHODS

Fourty farms along the Ebro Delta, Spain, were selected. Additionally in three of these farms, transects following various soil patterns were incorporated. Within these three farms, several fields were studied. A total of fifty fields (Fig. 6.1), including a wide range of environmental conditions (nutrients, weeds, diseases or pests), were monitored. Note that direct-seeded flooded rice is fully irrigated and water limitation is not commonly considered. These fields were surveyed and monitored during the rice growing season of 1995 and 50% of them in 1996.

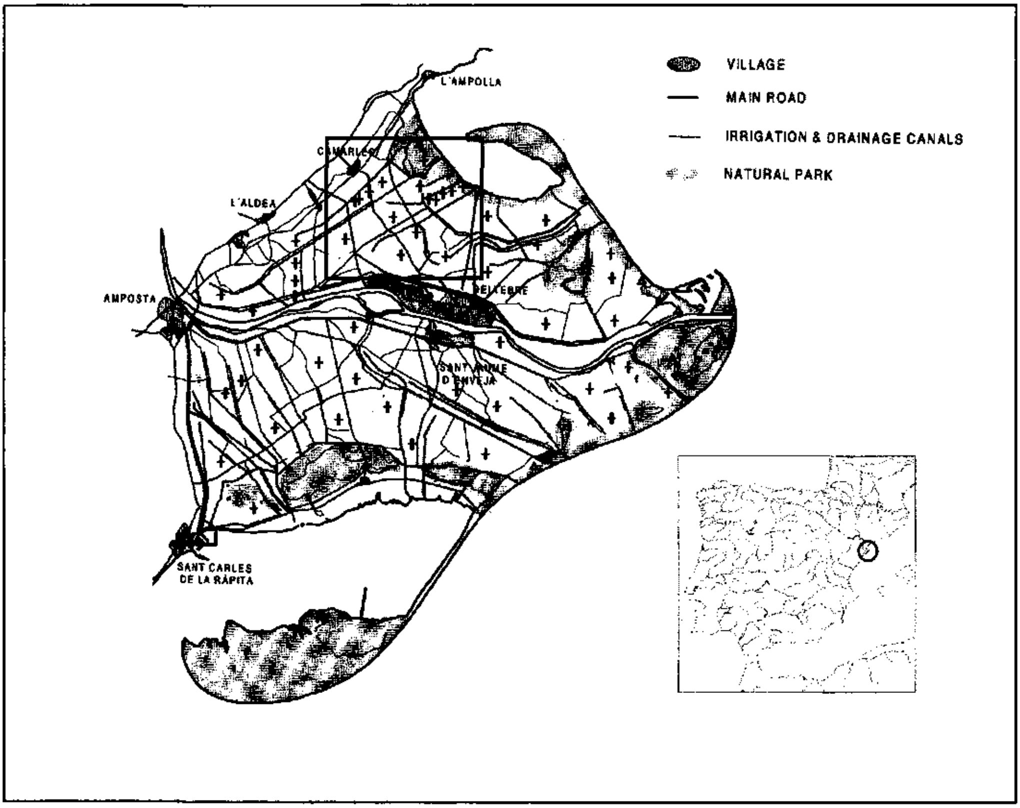

Fig. 6.1. Localization of the fields (+) on the Ebro Delta. The indicated part is enlarged in Fig. 6.3.

6.2.1. Soil, irrigation water and groundwater properties

The soil unit was classified at family level (SSS, 1996) joining together several concepts. In this case, these were:

- Soil type. The soil types of the study area were grouped based on:

(i) *profile development,* which was considered to occur if a histic horizon or calcium carbonate accumulation was present within 100 cm depth.

(ii) *coarse texture* (measured from the base of the Ap to 100 cm depth). A profile was considered to have coarse texture when a texture of loamy fine sand or coarser was found at any location in all the materials from the base of the epipedon to 100 cm depth.

Profile development and coarse texture were marked with 1 or 0 (as nominal-type of data) if present or not.

(iii) *drainage status.* Drainage status was ranked as ordinal attributes where determination in terms of greater or smaller is possible (Bregt, 1992), based on soil morphology and field measurements as shown in Fig. 6.2. The system ranged from 0 to 9, the increase corresponding with poorer soil drainage conditions based on:

- Redoximorphic features that are formed by the processes of reduction, translocation and oxidation of iron and manganese oxides in the soil after saturation and desaturation (Hseu and Chen, 1996).
- Reducing conditions characterized in the field with a neutral solution (pH=7) of α,α'-dipyridyl dye, which identified the presence of ferrous iron (Childs, 1981). The α,α'-dipyridyl solution was sprayed on freshly broken surfaces of field-moist soils where the presence of Fe(II) was indicated by a red (red wine) colour of the dye.
- Colours of the matrix that stand for "aeric" (SSS, 1996) which are either: a hue of 2.5Y or redder, a colour value, moist, of 6 or more, and a chroma of 3 or more; or a hue of 2.5Y or redder, a colour value, moist, of 5 or less, and a chroma of 2 or more; or a hue of 5Y and a chroma moist of 3 or more.

- Particle-size class. The clay percentage at 40-60 cm and 80-100 cm depth was measured.
- Topsoil texture as explained below in the granulometry of the epipedon.
- Soil salinity, expressed as averaged from 0 to 120 cm depth, was measured before flooding. Electrical conductivity values are commonly given in literature as EC_e. EC_e is a more reliable indicator for soil salinity than $EC_{1:5}$ because the dilution is lower and the moisture content of the sample is closer to the moisture content in reality (Porta and Ochoa, 1991). The saturated paste method, however, is more laborious than the $EC_{1:5}$. In selected samples, analyses of the saturated paste were performed.

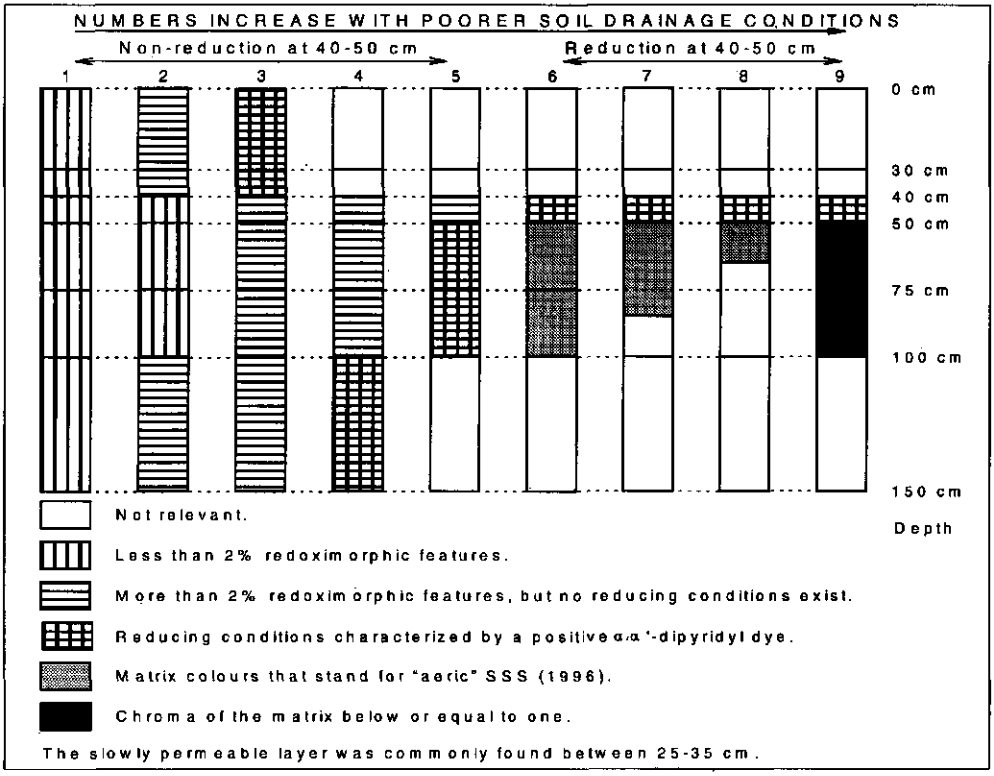

Fig. 6.2. Scheme for quantifying soil drainage status (surveyed on bare soils after the winter rains).

In the epipedon several properties were measured before flooding following the analytical methods recommended by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 1986):

- Granulometry (clay, silt and sand). It is determined by using appropriate sieves and pipettes.
- pH. It is determined potentiometrically by a pH-meter with a soil extract 1:2.5.
- Electrical conductivity. Measured from the extract of the saturated paste (EC_e) and from the extract of a soil/water suspension with a weight ratio of 1:5 ($EC_{1:5}$), Richards (1954). Because of soil salinity relevance in the study area, topsoil salinity was also measured at tillering.
- Cation exchange capacity and exchangeable potassium and magnesium. Extraction with ammonium acetate 1N at pH=7.
- Organic Matter content. Using the Walkey - Black method.
- Available Phosphorous. Using the Olsen - Watanabe method.
- Total N using the Kjeldahl method.
- Cations of the saturated extract; Na^+ and K^+ by photometry, Ca^{+2} and Mg^{+2} by absorption.
- Anions of the saturated extract. Chlorides, sulfates bicarbonates and nitrates by chromatography.

Texture and soil salinity are closely associated in the area, as shown in Fig. 6.3, which was obtained by interpolating 185 point values for percentage of clay in the topsoil and salinity averaged from 0 to 120 cm depth.

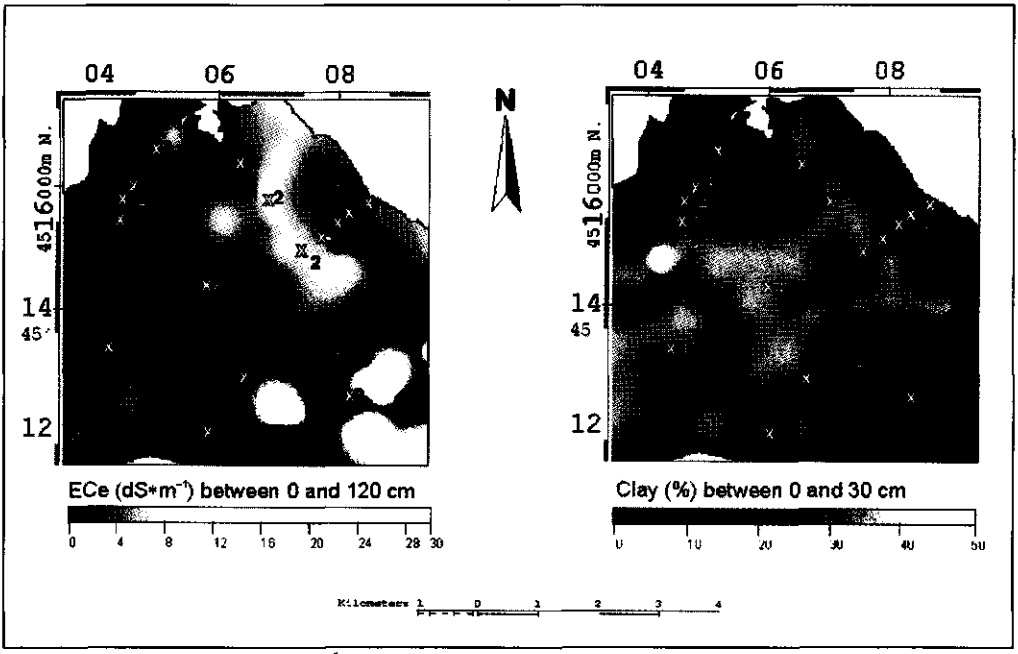

Fig. 6.3. **(a)** Soil salinity (dS m^{-1}) averaged from 0 to 120 cm (left side); **(b)** Topsoil clay (%) of the selected area (right side). Yields were measured at 16 locations. They are indicated in four classes, corresponding to the four quartiles (from the lowest, 1, to the highest, 4) shown in Table 6.1. High clay contents in the topsoil with low salinity gave the highest yields. High clay and salinity, found in old river courses and lagoon basins, gave moderate yields. The lowest yields were observed in coastal areas with sandy topsoils and profiles.

The electrical conductivity of the irrigation water at various sites during the growing season was measured. The groundwater table in the study area is shallow due to the absence of a gradient or natural drainage that would facilitate discharge to the sea (Bayó et al., 1992). Samples of the groundwater were taken and analysed; pH, electrical conductivity, sodium, calcium, magnesium, potassium, chloride, sulphate and bicarbonate.

6.2.2. Plant samples

Short cultivar types commonly grown in the study area were chosen such as Bahia, Senia, Tebre and Niva. Fields were visited at an approximately weekly basis during the rice growing season. The main phenological events such as panicle initiation, flowering and maturity were recorded. Visual weed and water management of the fields was recorded. Measurements and crop samples were taken at 3 sites with 3 replica's within the fields. A frame of 0.5 m^2 was used. At the ripening period; rice panicles, echinocloa species, cyperacea species and wild rice per square meter were measured. At maturity stage, the final yield components were measured: number of grains per panicle, percentage of filled spikelets, weight of 1000 dry-grains and moisture content of the grains. The fields were harvested independently by the farmer. For validating the farmer's data, at 30% of the parcels a final harvest of five square meter with three replicates in every field was collected. Reported yields refer to unmilled rice containing 14% water.

6.2.3. Data analysis

The variables in this study were not controlled nor preselected, in view of the fact that the experiments were run under field conditions. Thus, the levels of the independent variables can be considered random because they were not chosen at evenly spaced intervals.

Three main mathematical methods were used to describe and quantify the manner in which variables are related:

(i) Linear correlation analysis (Gomez and Gomez, 1984) was performed to show the degree of linear association between soil properties and yield values.

(ii) Linear regression was performed between the soil properties and the final yield values. The purpose of regression is to study the relationships among variables and to predict, or estimate, the value of a dependent variable from known or assumed values of other variables (Younger, 1979). To seek a statistical relationship between the different soil properties and rice yield, linear regression analysis was carried out, using a stepwise procedure. With stepwise regression, one starts with no explanatory variables. Step by step, variables are included if their inclusion significantly ($p \leq 0.05$) improves the quality of the model or excluded if their removal does not significantly decrease ($p \geq 0.1$) the quality of the model. A difference in input and output probability values avoids the situation that a variable is entered and removed in successive steps.

(iii) The Law of the Minimum of the limiting factors ("Min-Max" method), first proposed by Von Liebig (1855), was used for predicting yield from soil properties. As shown in Fig. 6.4, a scatter plot of an independent variable X_i with Y, a linear regression or a line over the maximum X-levels can be drawn. For the latter one, the steps followed are:

(1) Categorize the X_i variable in 10 groups.

(2) Select all the groups where $n > 2$.

(3) For every group, plot the histogram of the Y values and fit a normal distribution.

(4) For every group, select the X_i average and the Y at 95% confidence (mean plus two times the standard deviation).

(5) Fit a linear regression through these selected X_i and Y values.

This procedure is followed for every independent variable (i=1,2,...,N). These maximum lines $\{f(X_1), f(X_2), ..., f(X_N)\}$ can be considered imaginary "yield plateaus" as if this only variable was limiting Y. For every case, "N" fictitious Y's are derived. To determine the final Y, the minimum value achieved with all these maximum lines is chosen:

$$Y = \text{Min}\ \{f(X_1), f(X_2), ..., f(X_N)\} \qquad \text{(Eq. 6.1)}$$

where $f(X_1)$ = maximum attainable Y from the independent variable 1.
$f(X_2)$ = maximum attainable Y from the independent variable 2.
$f(X_N)$ = maximum attainable Y from the independent variable N.

Finally, only the independent variables needed to cover all the cases are selected. It is an operationalization of the von Liebig law where the limiting factors are estimated at the upper envelope of the datapoints.

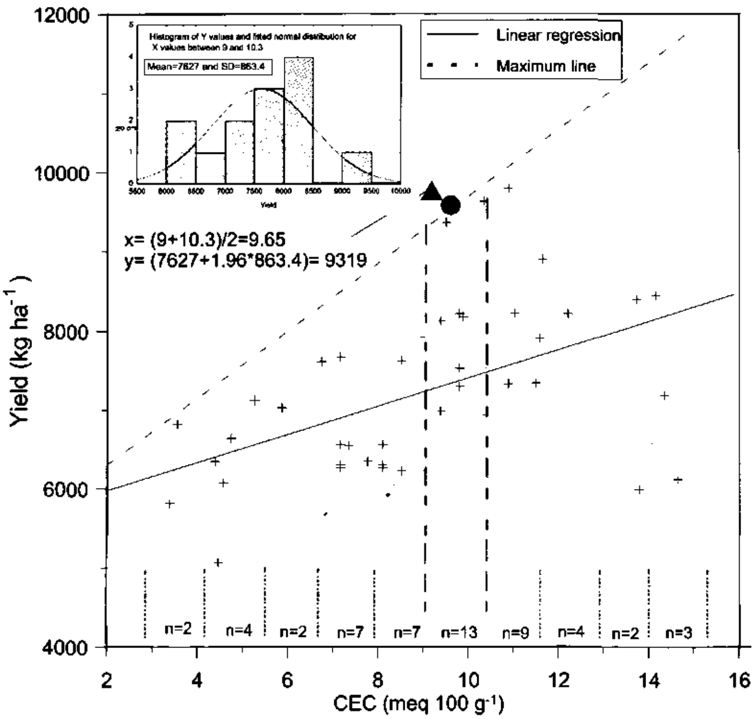

Fig. 6.4. Scatter plot of an independent variable Xi (here CEC in meq 100 g^{-1} as an example) and a dependent variable Y (yield in kg ha^{-1}). It shows the difference between the linear regression and the maximum line, illustrating the procedure for deriving the maximum line.

6.3. RESULTS

6.3.1. Basic statistical properties

Basic statistical properties of the soil and plant measurements within the study area are presented in Table 6.1. The rice yield varied spatially, ranging from 5000 to almost 11000 kg ha^{-1}, showing a high proportion of yields around 6500 and 7500 kg ha^{-1} (Fig. 6.5). The Liliefors test for normality, however, (test statistic equal to 0.0598, critical $w_{0.05}$ = 0.0886; see Connover, 1980) was not rejected. Therefore, the distribution of the yields over the area is close to normal. This was illustrated as well by the relatively low coefficient of variance (CV; 15%) and the small difference between the mean (7311 kg ha^{-1}) and the median (7300 kg ha^{-1}).

Table 6.1. Descriptive statistics for soil data and rice yield (n = 50). Profile development (1) and structure-less (0) soils; Coarse: coarse (1) and medium to fine (0); Clay1: clay (%) between 40-60 cm; Clay2: clay (%) between 80-100 cm; EC1: Soil salinity, averaged from 0-120 cm, before flooding (EC_e; dS m^{-1}); EC2: Topsoil salinity before flooding (EC_e; dS m^{-1}); EC3: Topsoil salinity before flooding ($EC_{1:5}$; dS m^{-1}); EC4: Topsoil salinity at tillering ($EC_{1:5}$; dS m^{-1}); CEC = cation exchange capacity; [1] indicates that the variable refers to the topsoil.

	Statistic*			Percentiles				
	Mean	SD	CV	Min.	25%	50%	75%	Max.
Yield (kg ha^{-1})	7311.2	1140.3	15.6	5068.5	6303.0	7300.0	8025.5	10601.0
Profile development	0.05	0.23	428.04	0.00	0.00	0.00	0.00	1.00
Coarse	0.18	0.38	218.72	0.00	0.00	0.00	0.00	1.00
Clay1 (%)	19.48	14.90	76.46	5.00	9.00	9.00	40.00	40.00
Clay2 (%)	15.82	11.92	75.34	5.00	5.00	9.00	26.50	40.00
Drainage	5.75	2.89	50.16	1.00	3.00	5.00	9.00	9.00
EC1	2.18	3.65	167.89	0.10	0.42	0.74	1.76	19.17
[1]EC2	4.29	2.41	56.19	0.95	2.67	3.53	5.56	10.87
[1]EC3	0.87	0.48	55.13	0.19	0.51	0.75	1.11	2.15
[1]EC4	0.54	0.23	42.19	0.10	0.41	0.49	0.59	1.50
[1]CEC (meq 100 g^{-1})	9.01	2.75	30.54	3.38	7.16	9.24	10.50	14.64
[1]Organic matter (%)	2.71	1.00	36.72	1.01	1.95	2.72	3.09	5.77
[1]Pavai.(ppm)	30.65	15.44	50.36	7.26	20.50	25.00	42.25	62.00
[1]Kexch.(ppm)	152.37	55.56	36.46	35.00	119.00	152.50	189.00	327.00
[1]Clay (%)	24.12	9.77	40.53	4.25	15.90	23.80	32.79	41.54
[1] Sand (%)	29.63	23.75	80.17	3.04	12.49	19.82	42.18	88.16
[1] Silt (%)	46.24	16.25	35.13	7.59	36.98	49.40	57.24	71.10
[1] pH	7.95	0.20	2.49	7.60	7.80	7.93	8.08	8.72
[1] Ntot (%)	0.15	0.05	34.72	0.04	0.12	0.15	0.18	0.29

* SD= standard deviation; CV= coefficient of variance

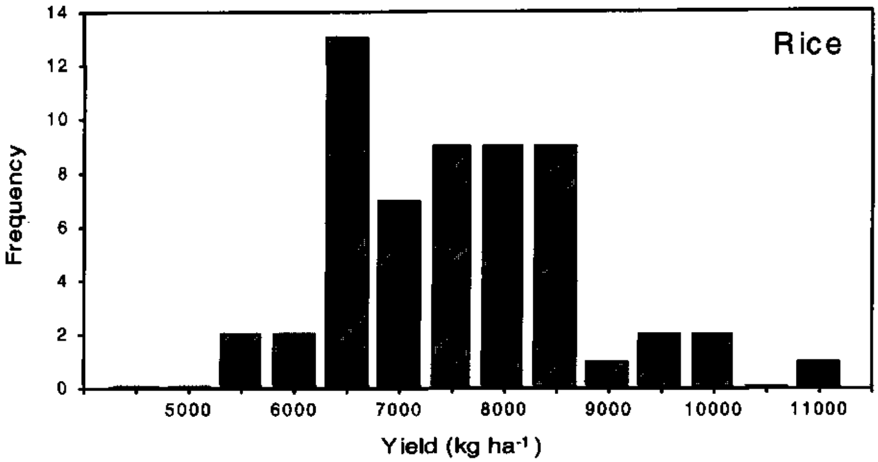

Fig. 6.5. Histogram of the distribution of rice yield in the selected parcels of the Ebro Delta.

Soil variables were distributed quite homogeneously, as is shown by CV values below 50%, with various exceptions: Profile development (CV = 452%) because most soils were structure-less; Coarse (CV = 201%), Clay1-2 (CV = 76-74%), Sand (CV = 80%) because the amount of soils with a sandy profile (typical of coastal areas) was low; EC1-2-3 (CV = 145-62-60%) because various soils (in particular at the old river courses and old lagoon basins) were highly salty but they occupy relatively small areas over the entire Ebro Delta (Chapter 3).

6.3.2. Quantification of soil properties, irrigation water and groundwater properties

Figure 6.6 shows the results of various selected soil horizons where electrical conductivity (EC) of the extract in the saturated paste and in a 1:5 dilution were measured. A linear relationship, independent of textural class, explained 92% of the variance. Results of the saturated paste showed that Na^+ and Cl^- in first terms, plus Mg^{2+} and SO_4^{2-} were highly correlated with the electrical conductivity.
The results of the soil salinity analysis were summarized in the classification of salt-affected soils (Richards, 1954) shown in Fig. 6.7. For sodium adsorption ratio (SAR) between 2 and 30, SAR and the exchangeable sodium percentage (ESP) are approximately equal. Non-saline soils, saline-sodic soils and saline soils were found. Non-saline sodic soils were not present in the study area. The saline soils were found in the low range of the saline-sodic soils, with either (i) a coarser texture down in the profile which allow high leaching of salts, or (ii) a better drainage status. The saline sodic soils, found mainly in the old river courses and basins of lagoons, reached maximum values of 30 dS m^{-1} averaged over the profile to 120 cm.

None of the soils had a pH of the saturated paste above 8.5, so they were not alkaline. A significant relation was found between pH of the extract at saturated paste (pH_p) and at 1:2.5 dilution ($pH_{1:2.5}$).

$$pH_p = 0.913 \times pH_{1:2.5} \qquad (n=42,\ r^2_{adj}=0.78) \qquad \text{(Eq. 6.2)}$$

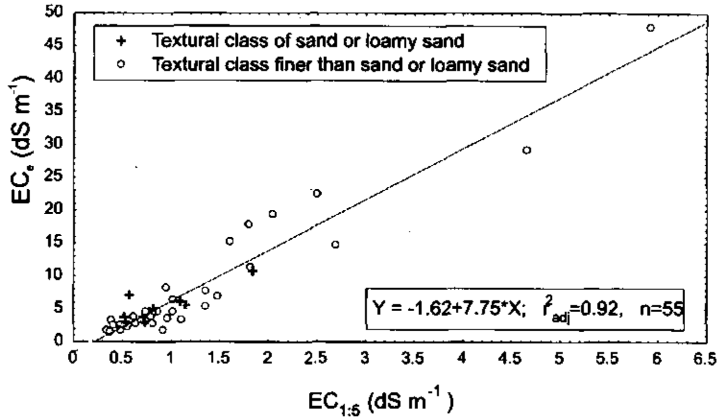

Fig. 6.6. Relationship between electrical conductivity of the extract in the saturated paste (EC_e) and of the extract in a weight dilution of 1:5 ($EC_{1:5}$) for various soil samples of the Ebro Delta. The slope has a standard error of 0.142 and a p-level < 0.001.

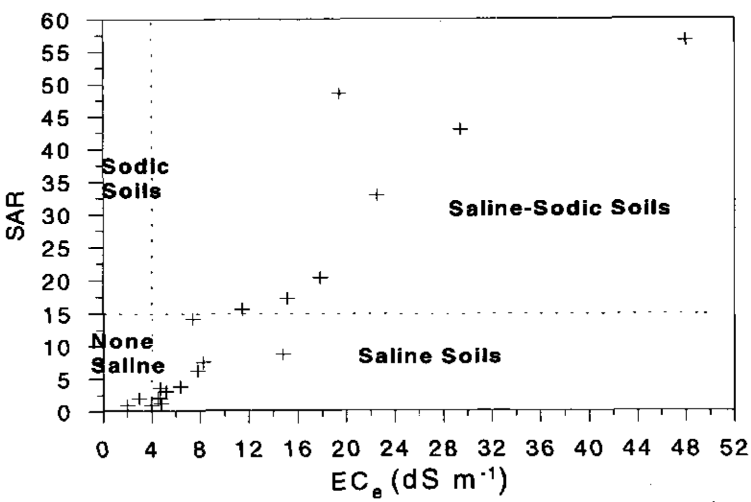

Fig. 6.7. Sodium adsorption ration (SAR) and electrical conductivity (EC_e) measured for various horizons (classified after Richards, 1954).

The measurements of the EC of the irrigation water during the growing season were on average 1.055±.088 dS m^{-1} (with maximum of 1.14 dS m^{-1}). In the northern side of the Ebro Delta (left bank), at three sites there was a recharge of drainage water to irrigation water, because of insufficient discharge of the irrigation channel. The electrical conductivity of the irrigation water, however, was always below 1.2 dS m^{-1}.

Groundwater analyses were performed because a significant relation between soil and groundwater salinity was expected. Equation 6.3 shows the results of the regression between the electrical conductivity of the soil saturated paste (EC_e) averaged from 0-120 cm and the electrical conductivity of the groundwater (EC_{gw}).

$$EC_e = 1.98 + 0.274 \times EC_{gw} \qquad (n=43,\ r^2_{adj} = 0.79) \qquad \text{(Eq. 6.3)}$$

The pH of the groundwater was on average 7.8±(2×0.2). All cations and Cl^-, as anion, were correlated with the electrical conductivity of the groundwater. SO_4^{2-} and HCO_3^-, however, saturated with the electrical conductivity at approximately 30 and 11 meq l^{-1} respectively. Figure 6.8 shows the scatter plot of the sodium adsorption ratio, SAR_{gw}, and the electrical conductivity, EC_{gw}, of the groundwater at various sites. Basically, three groups were distinguished:

(i) Groundwater of high EC (approx. 60 dS m^{-1}) and SAR (approx. 60). Found in the former river courses and lagoon basins that are highly saline.

The following two classes had a substantial difference in terms of EC and SAR, even though the two groups were not easily separated.

(ii) Groundwater of medium EC (approx. 10 dS m^{-1}) and SAR (approx. 25).

(iii) Groundwater of relatively low EC (approx. 4 dS m^{-1}) and SAR (approx. 6).

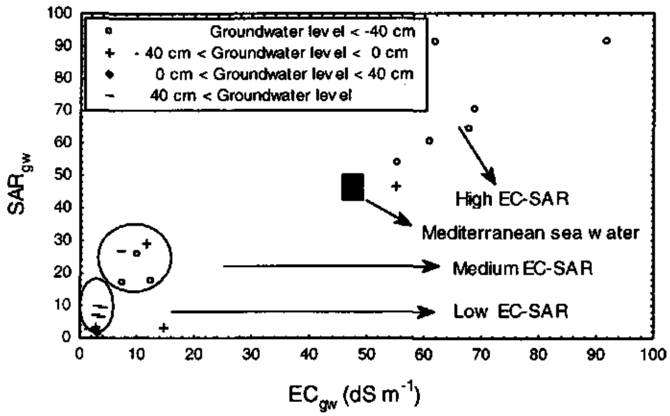

Fig. 6.8. Electrical conductivity and SAR of the groundwater at various sites on the study area. Groundwater level indicates the height of the groundwater over sea level in cm.

6.3.3. Prediction with correlation and regression analysis

To relate variability of yield to soil properties, we used the correlation coefficient (Table 6.2). Many variables had a significant correlation with rice yield, although none very high. The highest correlations were obtained for the clay content of the topsoil (r = 0.48) and related variables such as CEC, silt content of the topsoil and clay content at 40-60 cm. For n = 50 observations, a correlation is significant at the α = 0.05 level if it is higher than 0.28 or lower than -0.28. The negative correlation, observed at the so-called coarse variable, is caused by low clay percentage in the soil profile. Negative correlations were also observed for soil salinity measured in various manners, except in the topsoil at tillering.

Table 6.2. Correlation coefficients of rice yield (kg ha^{-1}) with soil variables. Profile development (1) and structure-less (0); Coarse: coarse (1) and medium to fine (0); Clay1: clay (%) between 40-60 cm; Clay2: clay (%) between 80-100 cm; EC1: Soil salinity, averaged from 0-120 cm, before flooding (EC_e; dS m^{-1}); EC2: Topsoil salinity before flooding (EC_e; dS m^{-1}); EC3: Topsoil salinity before flooding ($EC_{1:5}$; dS m^{-1}); EC4: Topsoil salinity at tillering ($EC_{1:5}$; dS m^{-1}); CEC = cation exchange capacity; [1] indicates that the variable refers to the topsoil.

Profile development	.37*
Coarse	-.37*
Clay1 (%)	.37*
Clay2 (%)	.29*
Drainage	.05
EC1	-.29*
[1]EC2	-.39*
[1]EC3	-.35*
[1]EC4	-.23
[1]CEC (meq $100g^{-1}$)	.46*,**
[1]Organic matter (%)	.13
[1]Pavai.(ppm)	.09
[1]Kexch.(ppm)	.17
[1]Clay (%)	.48*,**
[1] Sand (%)	-.41*
[1] Silt (%)	.31*
[1] pH	.39*
[1] Ntot. (%)	.22

*,** Significant at the 0.05 and 0.001 probability levels, respectively.

Next we applied a stepwise regression procedure to identify the soil variables with a significant influence on the variability of rice yield. The selected equations had the following form:

$$\text{Yield} = -16026.8 + 314.3\times\text{CEC} + 2736.5\times\text{pH} - 8573.2\times\text{Ntot};\ r^2_{adj} = 0.49 \quad \text{(Eq. 6.4)}$$

$$\text{Yield} = -14787.3 + 411.0\times\text{CEC} + 2525.6\times\text{pH} - 9830.7\times\text{Ntot} - 124.7\times[\text{Clay/Sand}];\ r^2_{adj} = 0.54 \quad \text{(Eq. 6.5)}$$

where CEC, pH, Ntot. and Clay/Sand are the corresponding values of the topsoil. These equations, although highly significant (F values of 15.9 and 13.9 with $v1$= 3 and 4 regressors and $v2$ = 47 and 46 degrees of freedom respectively), had a standard error of estimates equal to 752.3 and 727.0 for Eqs. 6.2 and 6.3, respectively. Adding a fifth variable, from any of the other soil properties, did not improve significantly the accuracy of the prediction. The major part of the variation could just be explained with three regressors, as shown, and could only slightly be increased with four regressors, despite its effect being significant.

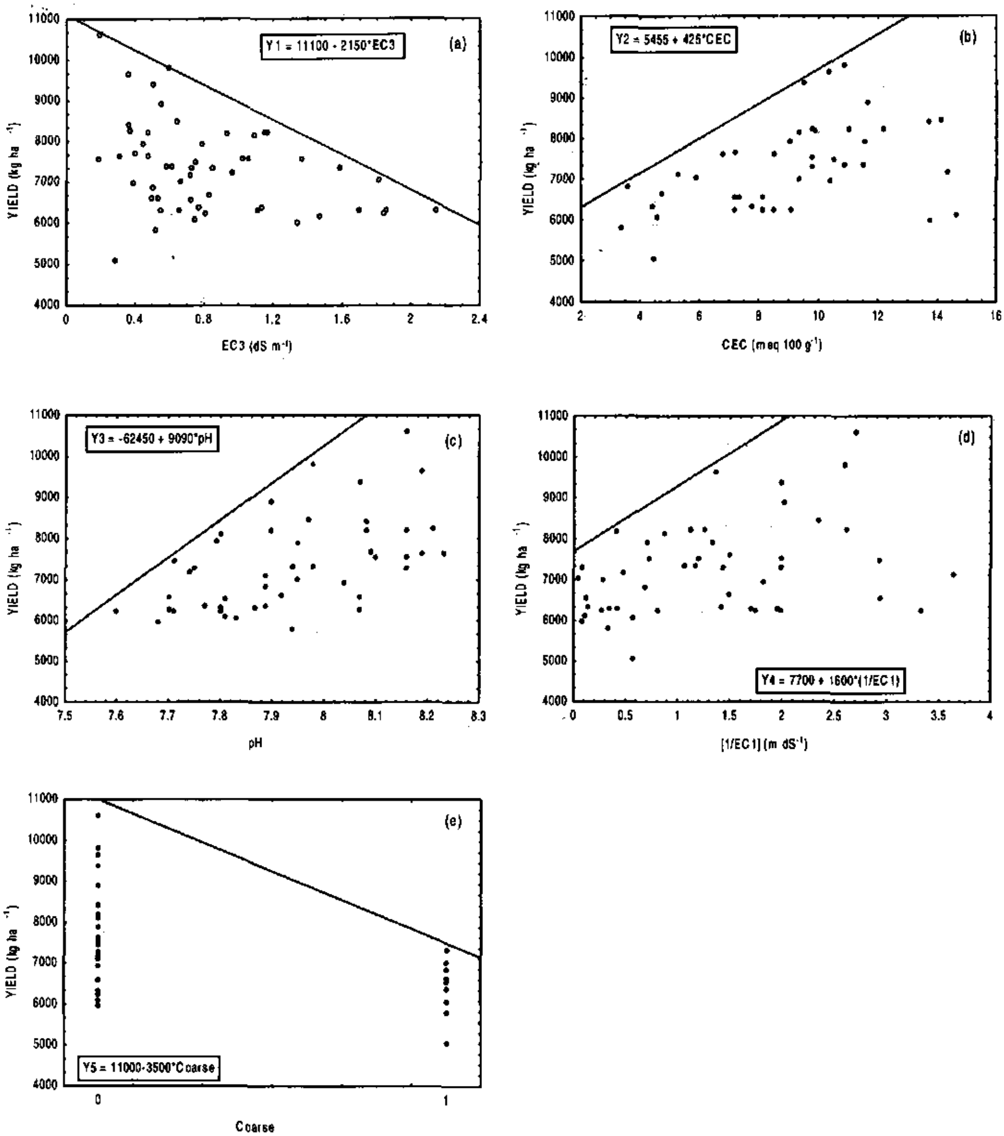

Fig. 6.9. Measured values in 1995 of rice yield and various soil variables; **a**-EC3 (electrical conductivity, $EC_{1:5}$, of the topsoil before flooding), **b**-CEC (cation exchange capacity of the topsoil), c-pH of the topsoil, **d**-Inverse of EC1 (electrical conductivity, EC_e, of the soil averaged from 0 to 120 cm) and **e**-coarse designates a texture of loamy sand or coarser in all the horizons from the base of the epipedon to 100 cm depth. The straight lines represent the maximum fitted lines.

6.3.4. Prediction with the "Min-Max" method

The relation of various soil variables with yield is shown in Fig. 6.9. The relation of soil salinity averaged from 0 to 120 cm (EC1) with yield had a negative exponential effect so that the inverse of EC1 was plotted. CEC and pH of the topsoil had a positive effect on yield, while the others had a negative effect. If a positive soil factor, such as CEC, has low values it limits yield; if values are average or high, then it does not limit yield, but other factors do. For a soil property with an adverse effect, it is the other way around. Additionally if such a soil property is zero, the upper limit reaches potential yield. Potential yield in the Ebro Delta is about 11000 kg ha^{-1} at field level (Chapter 4). In these scatter plots, straight lines over the maximum levels were drawn based on the "Min-Max" method. These lines (Y1, Y2, ..., Y_N) can be considered imaginary "yield plateaus" as if this only variable was limiting yield. Based on this assumption, an operational model was constructed for determining yield where five variables were sufficient, the ones shown in Fig. 6.9, to cover all the cases:

CEC = CEC (meq $100g^{-1}$) of the topsoil,
EC3 = Topsoil salinity ($EC_{1:5}$; dS m^{-1}) before flooding,
pH = Topsoil $pH_{1:2.5}$ before flooding,
EC1 = Soil salinity (EC_e; dS m^{-1}) averaged from 0 to 120 cm depth before flooding,
Coarse= a texture of sandy loam or coarser from the base of the epipedon to 100 cm is nominated with 1. if not it is 0.

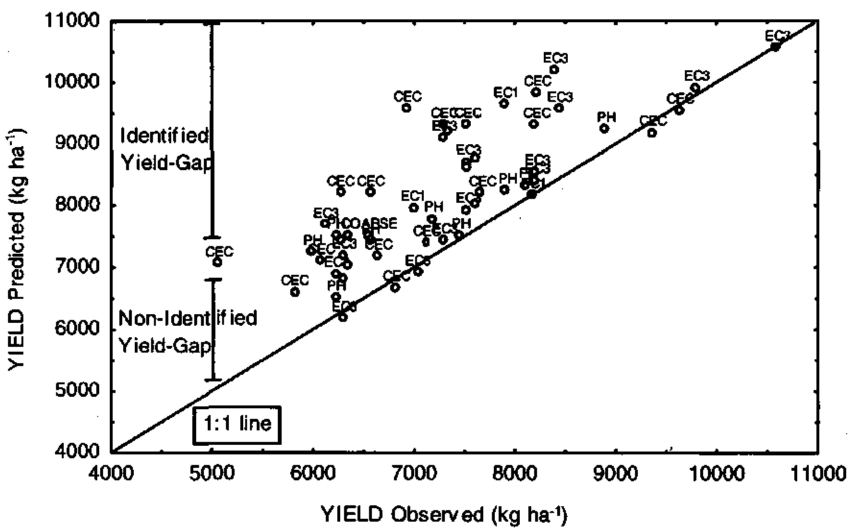

Fig. 6.10. Observed and predicted yield in 1995 from the "Min-Max" method using 5 soil variables with a r^2_{adj} = 0.58. Labels indicate the main limiting variable: EC3 (electrical conductivity, $EC_{1:5}$, of the topsoil before flooding), CEC (cation exchange capacity of the topsoil), pH of the topsoil, EC1 (electrical conductivity, EC_e, of the soil averaged from 0 to 120 cm) and Coarse designates a texture of loamy sand or coarser in all the horizons from the base of the epipedon to 100 cm depth.

Based on these five variables and the model of Eq. (6.1), yield was predicted as shown in Fig. 6.10. The calculated adjusted regression coefficient (r^2_{adj} = 0.58) was slightly higher than the one calculated in the multiple linear regression. Figure 6.10 illustrates graphically the identified and remaining (non-identified) yield gap. The identified yield gap was on average 2860 kg ha^{-1} and the remaining due to non-identified factors was 830 kg ha^{-1}. Figure 6.11 shows the prediction with multiple linear regression and "Min-Max" method simultaneously. Linear regressions between the predicted and observed values were fitted. In the latter one, yields were always higher or equal to the observed while in multiple regression the sum of the residuals was zero. Table 6.3 shows that the root mean square error of the prediction with the multiple linear regression was smaller (in the order of 10% of average yield).

The prediction and the observations were shifted to its own center point, so that the mean ($\bar{X}$,$\bar{Y}$) was subtracted from every value. Regression analysis between the difference of predicted values minus their mean ($Y-\bar{Y}$) versus the difference of observed values minus their mean ($X-\bar{X}$) is shown in Table 6.3. The intercept of the regression is now zero by definition. The slope in the "Min-Max" method was closer to one than in the multiple linear regression. The value of ($\bar{Y}-\bar{X}$) gave the mean bias of the prediction. ($\bar{Y}-\bar{X}$) was near zero in the multiple linear regression while it was between 800 and 1000 kg ha^{-1} in the "Min-Max" method. This was the average remaining yield gap.

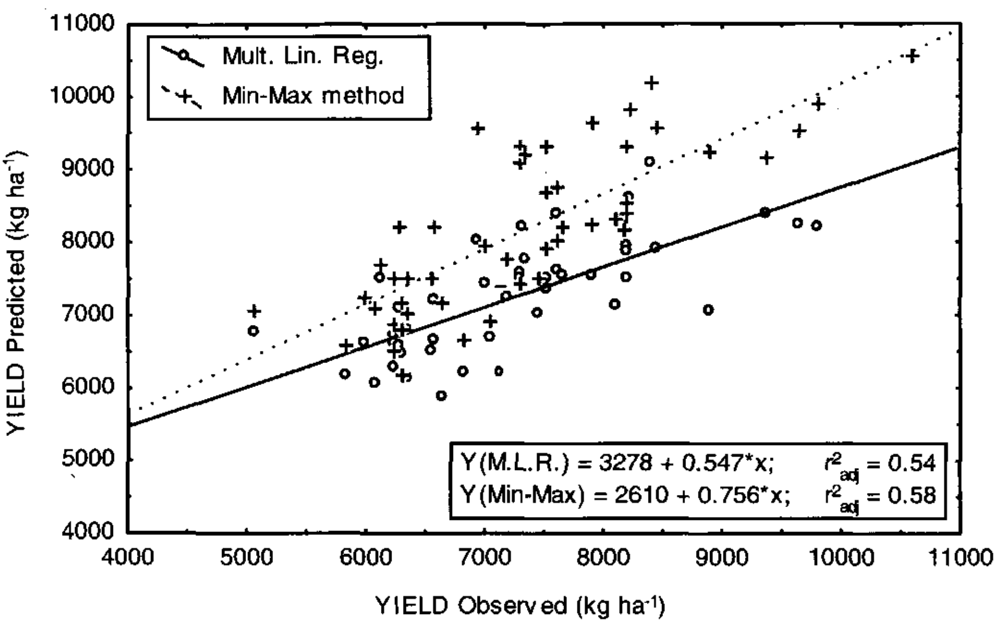

Fig. 6.11. Comparison of observed and predicted yields in 1995 with the multiple linear regression and the "Min-Max" method using 5 regressors (n=50).

Table 6.3. Regression analysis between the difference of predicted values minus their mean ($Y-\bar{Y}$) versus the difference of observed values minus their mean ($X-\bar{X}$) for rice yield with the 1995 dataset by using the "Min-Max" method and multiple linear regression (MLR) with 5 and 3 soil properties. In addition the root mean square error (RMSE in kg ha^{-1}) of the prediction is given. The random component of the prediction error is the difference between RMSE and the bias.

N=55 \Soil properties	Min-Max 5	Min-Max 3	MLR 4	MLR 3	OBSERVED
Mean (kg ha^{-1})	8140.4	8246.2	7238.4	7237.9	7311
Bias (systematic error)	829.2	935	-72.8	-73.3	
Slope	.756±.083	.745±.089	.547±.071	.504±.071	
	p=.005	p=.006	p=.000	p=.000	
r^2_{adj}	.60	.56	.54	.49	
RMSE (kg ha^{-1})	1089	1206	690	722	

6.3.5. Comparison with data from 1996

Relations observed in 1995 established between yield and soil variables were compared with 1996 where only few data (n=25) were available. The equations derived for predicting rice yield, were applied with the 1996 dataset. The regression equations between observed and predicted yields were:

$$Yp_{MLR} = 4313 + 0.42 \times Yobs\ ;\ r^2_{adj} = 0.50 \qquad \text{(Eq. 6.6)}$$

$$Yp_{M\text{-}M} = 4610 + 0.40 \times Yobs\ ;\ r^2_{adj} = 0.48 \qquad \text{(Eq. 6.7)}$$

where Yp_{MLR} stands for yield predicted with multiple linear regression and $Yp_{M\text{-}M}$ for yield predicted with the "Min-Max" method and Yobs for yield observed all in 1996. Both regressions were significant at the $\alpha = 0.05$ level. Thus, the same soil factors could explain the variance in yield the year after.

6.4. DISCUSSION AND CONCLUSIONS

6.4.1. Quantification of soil properties, irrigation water and groundwater properties

Drainage is very important in such a deltaic area (Pons and Zonneveld, 1965). Poor drainage conditions were associated with continuous rice cultivation (Moorman and Van Breemen, 1978) and with shallow groundwater tables (Bayó et al., 1992). When soil drainage conditions became poorer (from drainage class 1 to 9 of Fig. 6.2), first redoximorphic features were observed, followed by reducing conditions and, finally, matrix colours of low chroma (approx. 0). From drainage class 1 to 9, redoximorphic features were characterized by an;

- increased amount of Fe depletions (chroma <2) relative to the amount of Fe concentrations (chroma >6).
- increased amount of concentrations and depletions occurring along ped surfaces and matrix relative to the amount occurring around root channels.

The depth of saturation, as also mentioned by Hseu and Chen (1996), was very dynamic in the study area and was not considered useful for identifying aquic conditions and measuring soil drainage status.

The groundwater had effects over rice growth on the basis of:

- Depth. Results of this study showed that poor soil drainage conditions were not associated with rice growth. The effects of drainage on lowland rice are still controversial. Drainage during the cropping season, increased grain yield in various (e.g., Habibullah et al., 1977; Doi et al., 1988) but not all cases (Watanabe et al., 1974; Kogano et al., 1991). Ramasamy et al. (1997) found that higher yield response to nitrogen application was found under well-drained rather than under poorly-drained conditions. In this study area, however, some of the upper range rice yields were recorded in the poorly drained soils in the occidental areas where they have shallow groundwater tables due to seepage from adjacent uplands. It should be noted, however, that this groundwater corresponds to the low EC-SAR values of Fig. 6.8.
- "Quality" expressed as the electrical conductivity. In the study area the groundwater had a heterogeneous distribution. Old river courses and lagoon basins, even though small in area, formed channels of groundwater with very high electrical conductivity (60 dS m^{-1}). They seemed to behave as aquicludes reaching the groundwater values of the ratio Mg^{+2}/Ca^{+2} of 12, whereas the average Mediterranean-sea values are ratio of 3-5, (Libes, 1992; Custodio and Llamas 1983). These high ratios indicate that sea water, presumably, was the origin of this salinity. At the high and more occidental areas, recharge of fresh water pushed out or diluted the original saline groundwater whereas in the other areas, there was a process of salt reconcentration. Artificial drainage would be necessary for avoiding capillary rise from the groundwater in order to control salinization (Porta and Rodríguez-Ochoa, 1991). According to our results, benefits of artificial drainage such as control of soil water for better aeration, temperature and workability would be secondary factors in this study area.

6.4.2. Soil properties in relation to yield

Soil properties had a higher coefficient of variance than rice yield. This is in accordance with Trangmar et al. (1987), who found that the spatial variation of crop components had longer ranges than of soil properties. This result illustrates that in nature, plants tend to smoothen out differences in soil conditions.

Rice yield was highly correlated with soil properties. The main effects of soil properties on rice yield were grouped in:

(i) Positive effects of CEC, high clay and silt, and low sand contents. Similar results have been reported by other authors who relate these effects to (1) low fertilizer losses by leaching (Huang and Broadbent, 1988; Dobermann et al., 1996); (2) high concentrations of exchangeable cations (Trangmar et al., 1987) or (3) general fertility levels (Ishida and Ando, 1994). Lin (1984) considered CEC, K exchangeable as well as surface and subsurface texture inherent fertility constraints. The concentration of micronutrients, such as Zn, Mg, Ca, Mg, K, decreases under soil submergence (De Datta et al., 1988; Ahn et al., 1991) and especially with an increase in percolation rate. Properties that retain these nutrients are necessary for rice growth and a slow release is favourable as occurs at high CEC values. Fig 6.9b shows that at an approximate CEC value of 13 meq 100 g^{-1}, rice yield stabilizes and it is not a constraining factor anymore. Clay content is positively correlated with Zn content (Qi, 1987) and Zn shortage in the study area was reported in Chapter 7. To improve the chemical properties of coastal plain soils, various amendments have been reported including addition of Zeolite with a high CEC (Um et al., 1995). Correspondence of percentage clay with yields, as measured in 16 farms, is illustrated in Fig. 6.3.

(ii) Adverse effects of soil salinity. Soil salinity effects on rice growth have been reported widely in recent years (Khan et al., 1992a,b; Bohra et al., 1995). Singh et al., (1991) discusses the role of green manuring in reclamation of saline alkaline soils. In Chapter 7 of this thesis, it is found that in soils with high soil salinity, K and Zn absorption was hampered and only low levels of these cations were reached in the plant. In recent years, hypotheses about a chain of physiological events have been developed by Asch et al. (1995): High soil electrical conductivity reduces stem base water potential, followed by release of root-borne abscisic acid to the xylem eventually resulting in stomatal closure. Our results are in accordance with that literature showing that soil salinity reduces crop growth, even under fully irrigated lowland rice with a 15 cm layer of irrigation water of good quality (<1.0 dS m^{-1}) during the growing season on the soil surface. Correspondence of soil salinity with yields, as measured in 16 farms, is illustrated in Fig. 6.3.

(iii) Positive effects of pH. Similar positive effects of soil pH on yield were found by Dobermann (1994). This author even proposed soil pH as a criterion for soil fertility mapping in their study area. Negative correlations with rice yield have been reported by other authors (Kant and Kumar, 1992; Dubey et al., 1987), but these were especially for alkaline soils (pH>9.5). As shown in Fig. 6.7, alkaline soils were not found in this area. Only saline-sodic soils occurred with a maximum $pH_{1:2.5}$ of 8.8. Figure 6.9c shows that at an approximate $pH_{1:2.5}$ value of 8.1, rice yield stabilizes and it is not a constraining factor anymore. Within the range of 7.6 to 8.8 ($pH_{1:2.5}$) the effect of pH was positive in our study. This corresponds with a range of 6.94 and 7.94 when considering pH of the saturated paste.

6.4.3. The "Min-Max" method and the multiple linear regression

The statistical procedures used, focused on relations with field conditions. In the "Min-Max" method, the starting point is that positive factors, such as the CEC, are needed to produce high yields. Negative factors act as loss terms. Additionally, if such negative properties are zero, the upper limit reaches potential yield. Dobermann (1994) found that regression models based on soil properties explained 56% of rice yield variation. This result was similar to our findings. That same author suggested co-spatial soil and crop survey and application of multivariate statistics as suitable methods for exploration of complex soil-crop interactions. This may be true, but making statistical calculations much more complicated than the ones presented here, may not yield worthwhile additional results.
The regression coefficient between predicted and observed values in both the, multiple linear regression and "Min-Max" method, were similar with a slightly better result for the "Min-Max" method. Multiple linear regression, however, had a lower (systematic) bias, and a larger random component. Once the systematic error is known (its overestimation or unexplained yield gap, 800-1000 kg ha^{-1}), the "Min-Max" method allows a more accurate prediction and a smaller random component (see Table 6.3).

6.5. ACKNOWLEDGMENTS

This work was carried out as part of the project of the Commission of the European Communities number: ERB-4001-GT931494. It is part of the core research programme of the "Rice Network" within the "Global Change and Terrestrial Ecosystem" of the IGBP. We are grateful to the staff of the IRTA experimental station in the Ebro Delta for providing data for this paper. Thanks are also due to Mr. J. Llop, Mr. J. Racó, Mr. J. Rebull and Mr. A. Forcadell for their field measurements.
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Quantitative analysis of yield and its determining factors

Abstract:
This article aims to quantify rice growth at field level in relation to the status of the plant and soil properties in irrigated direct-seeded rice. A total of 40 fields spread along the Ebro Delta (Spain) were selected. Rice growth was monitored and soil properties were measured. Yield was related to soil properties by a deductive process identifying the yield determining factors. First (i) yield components, then (ii) variables related to cropping status and finally (iii) soil properties were identified. To interrelate the different groups of variables, correlation analysis and an operationalization methodology of the Law of the Minimum, first proposed by Von Liebig, were used. To quantify yield at field level, besides panicle and spikelet number, the fraction of grains with necrosis (quality of the grains), the intensity of weed infestation and the spatial heterogeneity within fields were necessary. Yield prediction accuracy from these five variables was very high, r^2_{adj} = 0.94. Four main groups of causes limited rice growth: (i) potassium and (ii) zinc shortage where a strong antagonism of either factor with sodium was observed, (iii) low plant establishment where a minimum number of 160-180 plants m^{-2} was necessary to maximize yield, and (iv) length of the growing season, especially the length of the pre-heading period in which the potential size of the crop yield is primarily determined. Yield prediction accuracy from these variables was moderately high, r^2_{adj} = 0.76. The larger the causal distance between yield and its determining factors, the lower the prediction accuracy. Potassium and zinc shortages in the plant were mainly induced by soil salinity. Zinc shortage was not related to high soil pH. High K in saline soils did not increase K uptake. It remains to be determined if addition of Zn increases Zn uptake in the saline soils of the study area. The length of the growing period was primarily determined by temperature, but also by soil properties. A high clay content of the topsoil favoured long growing cycle, homogeneity of plants per unit area, and adequate potassium and zinc levels in the plant.

Keywords: Rice; Soil salinity; Na; K; Zn; Plant density; Cropping status; Ebro Delta.

Submitted to "Field Crops Research": Casanova, D., Goudriaan, J., Catala Forner, M.M., Withagen, J.C.M.. Quantitative analysis of yield and its determining factors in direct-seeded flooded rice.

7.1. INTRODUCTION

Rice is cultivated throughout the world in many different ways and degrees of intensification. Main cropping differences exist between upland rice and lowland rice. Lowland rice may be irrigated or rainfed. Under fully irrigated conditions, rice may be transplanted or direct seeded. Direct seeded under irrigation is the most common form in Europe, Australia and USA (Hill et al., 1991). Rice cultivation in the Ebro Delta (north-east Spain) occupies an average area of 21000 ha with an average yield of 6500 kg ha^{-1} (Catalá Forner and Fosch, 1997). This article focuses on the understanding of rice growth in relation to plant status and soil properties in irrigated, direct-seeded rice in the Ebro Delta.

The potential yield of a rice crop is determined only by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation. Under optimum growth conditions, light, temperature and varietal characteristics for phenological, morphological and physiological processes are the main factors determining the growth rate of the crop on a specific day (Kropff et al., 1994). Under growth limiting conditions, soil properties have an effect on nutrient absorption by the plant which will be reflected in the plant status (Matsushima, 1957; De Datta, 1981; Patrick et al., 1985). This plant status is associated with physiological processes that determine rice growth and yield.

A total of 40 fields spread along the Ebro Delta were selected (see Fig. 7.1). Rice growth was monitored and soil properties were measured. In agricultural sciences, research is usually done by selection of one field with different subplots where all the variables except one are similar. The response of the crop to this dissimilar variable is measured and quantified in a straightforward manner (Gomez and Gomez, 1984). This chapter tackles the problem in a rather different way by observing directly what is happening in the field. Such an approach is often followed by sociologists, biologists, epidemiologists, etc. It exploits and analyzes the available environmental variability and its effects (Webster and Oliver, 1990), instead of explicit experimentation. By no means we believe this methodology to be the best one; it is just considered to be an alternative approach.

For identifying and quantifying the main soil properties that limit rice production, the scheme shown in Fig. 7.2 is followed. The causal chain goes from right to left; soil properties and farm management influence the cropping status which together with weather conditions have effects on growth, that finally determines yield. Ideally, there should be a processed-based model to relate soil properties with rice growth. Unfortunately no complete one exists, and therefore a deductive process is followed that goes from left to right in Fig. 7.2:

(1) First of all, yield was related to yield components. As an example, if a field had lower production than another, it might be (i) because it had a smaller number of spikelets or (ii) it had a similar number of spikelets but a smaller fraction of filled spikelets. The first step was to identify the main yield components and some adverse factors determining yield.

(2) The second step was divided in two in order to emphasize the interrelationships between plant growth and cropping status. By cropping status we mean crop establishment, crop duration and nutrient status with the standard N-P-K as well as Zn, Fe, Mn, Mg, S, Cu, B, Na, and Ca. Step (2a) related yield components and adverse factors with cropping status. Step (2b) identified the main variables of the cropping status that were related directly to yield. Step (2b) can be considered a validation of Steps 1 and (2a), so that the significant variables in both approaches should be the same.

(3) Finally, the cropping status was related to the soil properties to find out which had effects and in what terms, e.g. soil salinity may reduce potassium uptake, while a poor drainage condition may reduce the germination percentage inducing a low plant establishment. In this step-by-step approach, finally we were able to identify what and how soil properties affected rice growth.

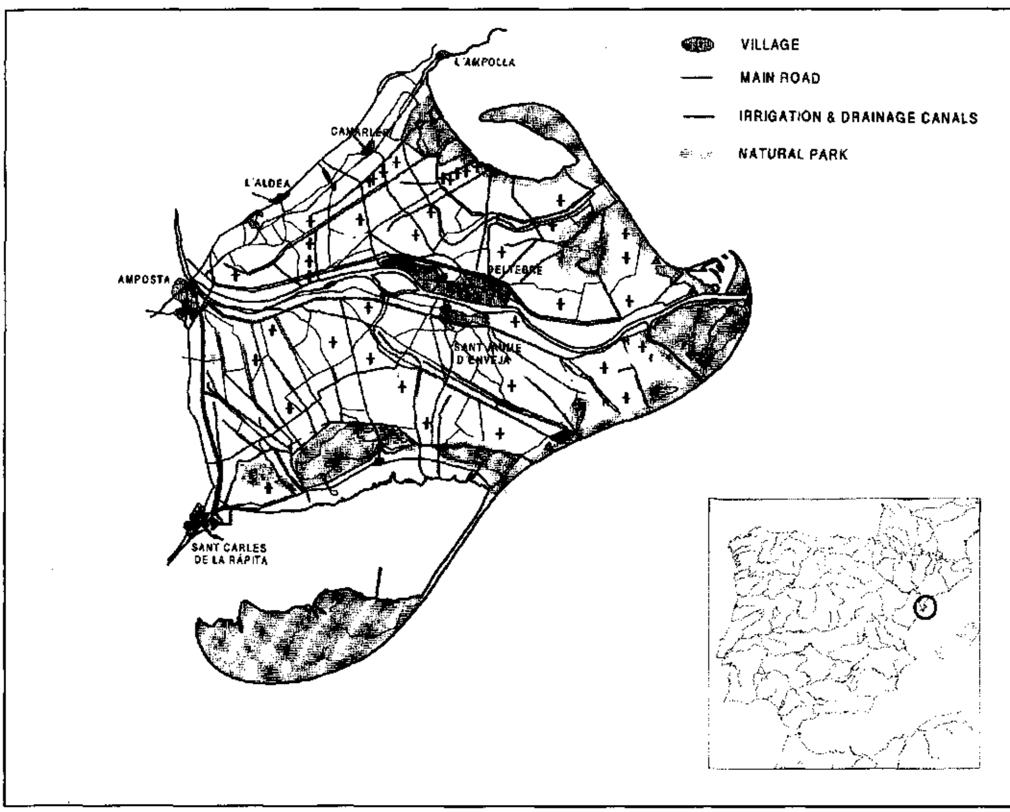


Fig. 7.1. Localization of the fields (+) within the Ebro Delta.

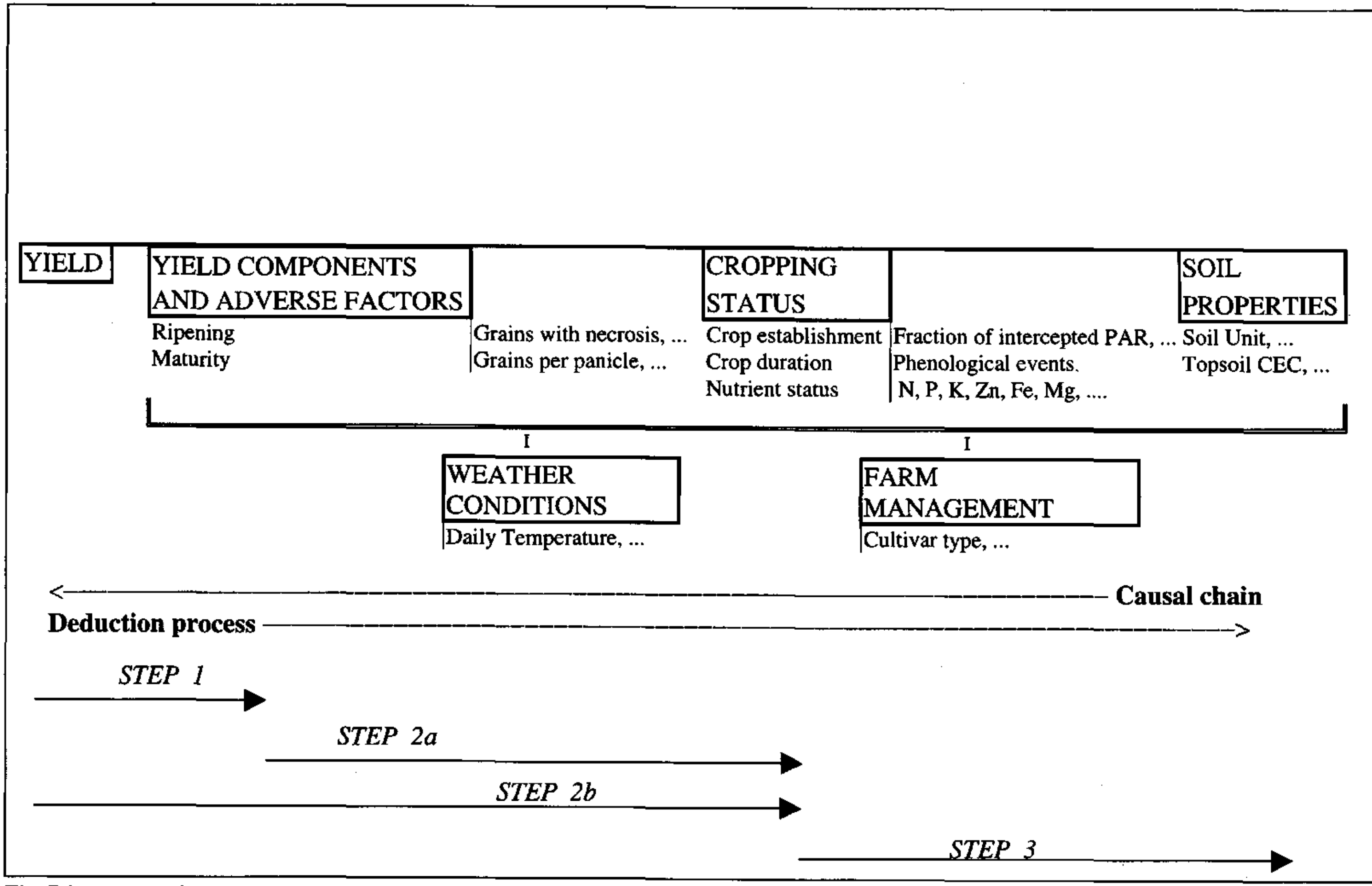


Fig. 7.2. Scheme of the methodology followed to relate yield to soil properties.

7.2. MATERIALS AND METHODS

Thirty farms along the Ebro Delta, Spain, were selected. Additionally in three of these farms, transects following various soil patterns were incorporated. Within these three farms, several fields were studied. A total of fourty fields (Fig. 7.1), including a wide range of environmental conditions (nutrients, weed, disease or pest), were monitored. Note that direct-seeded flooded rice is fully irrigated and water limitation is not commonly considered. These fields were surveyed and monitored during the rice growing season of 1995. The variables studied were grouped in the scheme presented in Fig. 7.2.

7.2.1. Soil sampling and analyses

The soil unit was classified at family level (SSS, 1992) joining together several concepts. In this case, these were (i) soil type, (ii) particle-size class, (iii) topsoil texture, and (iv) soil salinity. The soil types of the study area were grouped based on profile development, coarse texture (from the base of the Ap to 100 cm depth) and drainage status (Chapters 3 and 6). Profile development and coarse texture, as nominal data, were marked with a 1 or a 0 if presence or not of in-situ development and a texture of loamy fine sand or coarser in all the materials from the base of the epipedon to 100 cm, respectively. A system to quantify soil drainage status was developed based on soil morphology and field measurements. It ranged from 0 to 9, the increase corresponding with a poorer soil drainage conditions. The rest of soil properties were considered ratio type of data with a true zero. The soil salinity, averaged from 0 to 120 cm depth, was measured before flooding.

In the epipedon several properties before flooding were measured following the analytical methods recommended by the Spanish Ministry of Agriculture, Fisheries and Food (MAPA, 1986):

- Granulometry (clay, silt and sand). It is determined by using appropriate sieves and pipettes.
- pH. It is determined potentiometrically by a pH-meter with a soil extract 1:2.5.
- Electrical conductivity. Measured from the extract of the saturated paste (EC_e) and from the extract of a soil/water suspension with a weight ratio of 1:5 ($EC_{1:5}$), Richards (1954). Because of soil salinity relevance in the study area, topsoil salinity was also measured at panicle initiation stage.
- Cation exchange capacity and exchangeable potassium and magnesium. Extraction with ammonium acetate 1N at pH=7.
- Organic Matter content. Using the Walkey - Black method.

- Available Phosphorous. Using the Olsen - Watanabe method.
- Total N using the Kjeldahl method.

7.2.2. Farm management

Farm management practices were recorded in time, including land preparation, fertilizer (N-P-K) basal and cover, sowing (date and dose), cultivar type, weed management (chemical application or mechanical), fungi management, harvesting date, post-harvesting practices (burning or incorporating the straw in the field). Short-grain cultivar types commonly grown in the study area were chosen such as Bahia, Senia, Tebre and Niva.

7.2.3. Weather conditions

Daily totals of temperature, global short-wave radiation and wind speed were measured at an agricultural experiment station situated in the study area, 15 km from the river mouth.

7.2.4. Nutrient status

Crop samples were taken at tillering and at maturity stage. The following nutrients in the different plant components were analyzed; at tillering in the leaves (N and P), at tillering in the stems (Ca, Na, Zn, K and Mg), and at maturity in the straw and grains (N, P, K, Ca, Na, Zn and Mg). In addition at 20% of the fields at tillering, various nutrients at different plant components were measured; leaves (Ca, Na, Zn and Mg), stems (N and P) and in both leaves and stems (S, Fe, Mn, Cu and B).

7.2.5. Plant sampling and measurement of growth and yield values

Fields were visited at an approximately weekly basis during the rice growing season. The main phenological events such as panicle initiation, flowering and maturity were recorded. Weed and water management of the fields were visually recorded. Measurements and crop samples were taken at three sites with three replicates within the fields. A frame of 0.5 m^2 was used. The plant characteristics measured were grouped based on the rice development stage:

(i) At early tillering. Number of plants per square meter were measured. The fraction of intercepted photosynthetically active radiation (PAR), f_{PAR}, was calculated (Chapter 5) from field reflectance measurements taken with a hand-held multispectral radiometer (CROPSCAN Inc., 1993). An optimum f_{PAR} for potential production was derived from ORYZA1, a physiological model (Kropff et al., 1994), based on development stage. The difference between the optimum and the measured f_{PAR} was introduced in the matrix data. This variable gives an estimate of the deviation from the most adequate f_{PAR} that the field should have at that moment. It can be thought of to be a measure for a "good start" for the rice crop.

(ii) At flowering. Reflectance measurements saturate and are inadequate for deriving high values of f_{PAR} (Chapter 5). Therefore, direct measurements of PAR (400-700 nm) above and below the canopy were performed with the Decagon Sunfleck Ceptometer (Model SF-80, Decagon Devices, Inc. 1989). The instrument has 80 light sensors placed at one-centimeter intervals along a probe. A microprocessor scans the 80 sensors and computes an average reading on command. These f_{PAR} values at flowering are, up to a certain extent, a measure of the source capacity of the rice plant.

(iii) At ripening. Plant samples were taken from the fields and various characteristics were investigated: number of green leaves at hard dough stage, fraction of leaf area affected by *Helminthosporium*, *Pyriculariosis* or other disorder, fraction of shoots affected by black (probably *Fusarium* spp.) or brown (probably *Sclerotium* spp.) disorders and fraction of grains affected by necrosis or *Pyriculariosis*. Additionally rice panicles, *Echinocloa* spp., *Cyperacea* spp. and wild rice per square meter were measured. Plant height was also recorded.

(iv) At maturity. To perform the final yield components analysis, the following variables were measured; number of grains per panicle, percentage of filled spikelets, weight of 1000 dry-grains and moisture content of the grains. The percentage of filled spikelets was determined from the number of unmilled grains that sank in a saline solution with a specific gravity of 1.06, in relation to the number of spikelets (Matsushima, 1957). The fields were harvested independently by the farmer. For validating the farmer's data, at 20% of the fields a final harvest of five square meter with three replicates in every field was collected. Reported yields refer to unmilled rice containing 14% water.

Maturity stage is defined as the time when the maximum grain weight is attained (Yoshida, 1981), independently from harvesting date. To estimate maturity stage, a model based on the temperature summation concept was used (Chapter 4). The input variables were the moisture content at harvesting date and the daily temperature. Maturity stage was assigned to a final moisture content of the grains equal to 25.5%.

7.2.6. Data analysis

The variables in this study were not controlled or preselected, in view of the fact that the experiments were run under field conditions. Thus, the levels of the independent variables can be considered random because they were not chosen at evenly spaced intervals.

A method for examining grain yield performance is to break the yield into its components:

$$Y = PANO \times SPP \times FSP \times W_f \times 10^{-7} \qquad \text{(Eq. 7.1)}$$

where Y = grain yield ($t\ ha^{-1}$)
PANO = panicle number m^{-2}
SPP = spikelet per panicle
FSP = fraction of filled spikelets
W_f = 1000-full grain weight (g)

In Eq. 7.1, the spikelet number includes filled, partially filled and unfertilized spikelets. The filled spikelet is called grain. The fraction of filled spikelets is a ratio of the number of grains to the total number of spikelets. The 1000-grain weight is the average weight, in grams, of 1000 grains.

Two main mathematical methods were used to describe and quantify the way in which variables are related:

(i) Simple linear correlation analysis (Gomez and Gomez, 1984) was performed to show the degree of linear association between soil properties and cropping status in Step 3 and the response in yield components and adverse factors to cropping status in Step (2a). In addition, simple linear regressions were fitted between the predicted and observed variables.

(ii) The Law of the Minimum of the limiting factors ("Min-Max" method), first proposed by Von Liebig (1855), was used for predicting yield in Step 1 and Step (2b) from yield components (and some adverse factors) and the cropping status, respectively. As shown in Fig. 7.3, a scatter plot of an independent variable X_i with Y, a linear regression or a line over the maximum X-levels can be drawn. For the latter one, the steps followed are:

(1) Categorize the X_i variable in 10 groups.
(2) Select all the groups where n >2.
(3) For every group, plot the histogram of the Y values and fit a normal distribution.
(4) For every group, select the X_i average and the Y at 95% confidence (mean plus two times the standard deviation).
(5) Fit a linear regression through these selected X_i and Y values.

This procedure is followed for every independent variable (i=1,2,...,N). These maximum lines $\{f(X_1), f(X_2), ..., f(X_N)\}$ can be considered imaginary "yield plateaus" as if this only variable was limiting Y. For every case, "N" fictitious Y's are derived. To determine the final Y, the minimum value achieved with all these maximum lines is chosen:

$$Y = \text{Min}\ \{f(X_1), f(X_2),\ ...,\ f(X_N)\} \qquad \text{(Eq. 7.2)}$$

where $f(X_1)$ = maximum attainable Y from the independent variable 1.
$f(X_2)$ = maximum attainable Y from the independent variable 2.
$f(X_N)$ = maximum attainable Y from the independent variable N.

Finally, only the independent variables needed to cover all the cases are selected. It is an operationalization of the Von Liebig law (the thirty-third statement of the "Principles of Agricultural Chemistry") where the limiting factors are estimated at the upper envelope of the datapoints. This method was used instead of multiple linear regression because of higher prediction accuracy (as shown in Chapter 6).

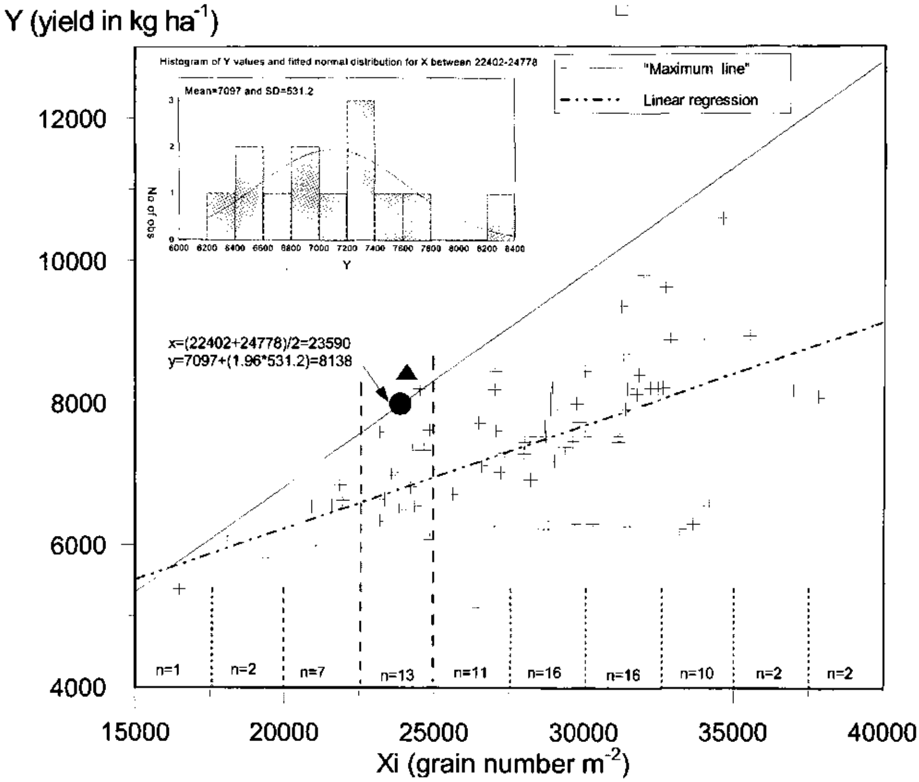


Fig. 7.3. Scatter plot of an independent variable Xi (here grain number m^{-2} as an example) and a dependent variable Y (yield in kg ha^{-1}). It shows the difference between the linear regression and the maximum line.

7.3. RESULTS

Yields derived from Eq. 7.1 (average of 8786 kg ha^{-1}), measured with three replicates of a 0.5 m^2 frame, were larger than yields derived at field level (these are similar to the ones measured with three replicates of a 5 m^2 frame). Furthermore, the average observed yield at field level (7467 kg ha^{-1}) was higher than the Ebro Delta average as a whole (MAPA, 1995; 6500 kg ha^{-1}). This indicated that either good fields were overselected, or that the chosen farmers put extra effort in their fields being conscious of our objectives, or that average production calculated at the Spanish Ministry of Agriculture has a certain error.

7.3.1. Deducting significant yield components and some adverse factors from yield values (Step 1).

The relation of five plant characteristics (two yield components and three adverse factors) to yield is shown in Fig. 7.4. The yield components had a positive effect on yield. If a yield component has low values it limits yield; if values are average or high, then it does not limit yield, but other factors do. For a plant characteristic with an adverse effect, it is the other way around. Additionally if such a characteristic is zero, the upper limit reaches potential yield. In these scatter plots, straight lines over the maximum levels were drawn based on the "Min-Max" method. These lines (Y_1, Y_2, .., Y_N) can be considered imaginary "yield plateaus" as if this only variable was limiting yield. Based on this assumption, an operational model was constructed for determining yield where five variables were sufficient to cover all the cases:

PANO = panicles per square meter,
SPNO = spikelets per square meter,
GN = percentage of grains with necrosis (variable estimated during ripening),
FFD = standard deviation in f_{PAR} at flowering (a measure of heterogeneity), and
WI = intensity of weed infestation (sum of *wild rice*, *Echinocloa* spp. and *Cyperaceas* spp. at ripening).

Other yield components such as the fraction of filled spikelets, the 1000-full grains weight and the spikelets per panicle (per se) were not significant in this analysis. Based on these five variables and the model of Eq. 7.2, yield was predicted (Fig. 7.5a). The intercept was not significantly different from 0 (p>0.05) and the slope was not significantly different from 1 (p>0.05). Figure 7.5b illustrates the observed and predicted yield with only the two yield components. The predictions were accurate for high values but not for low. Rice necrosis, spatial heterogeneity and weeds infestation, when present, had a strong effect but were not reflected in the yield

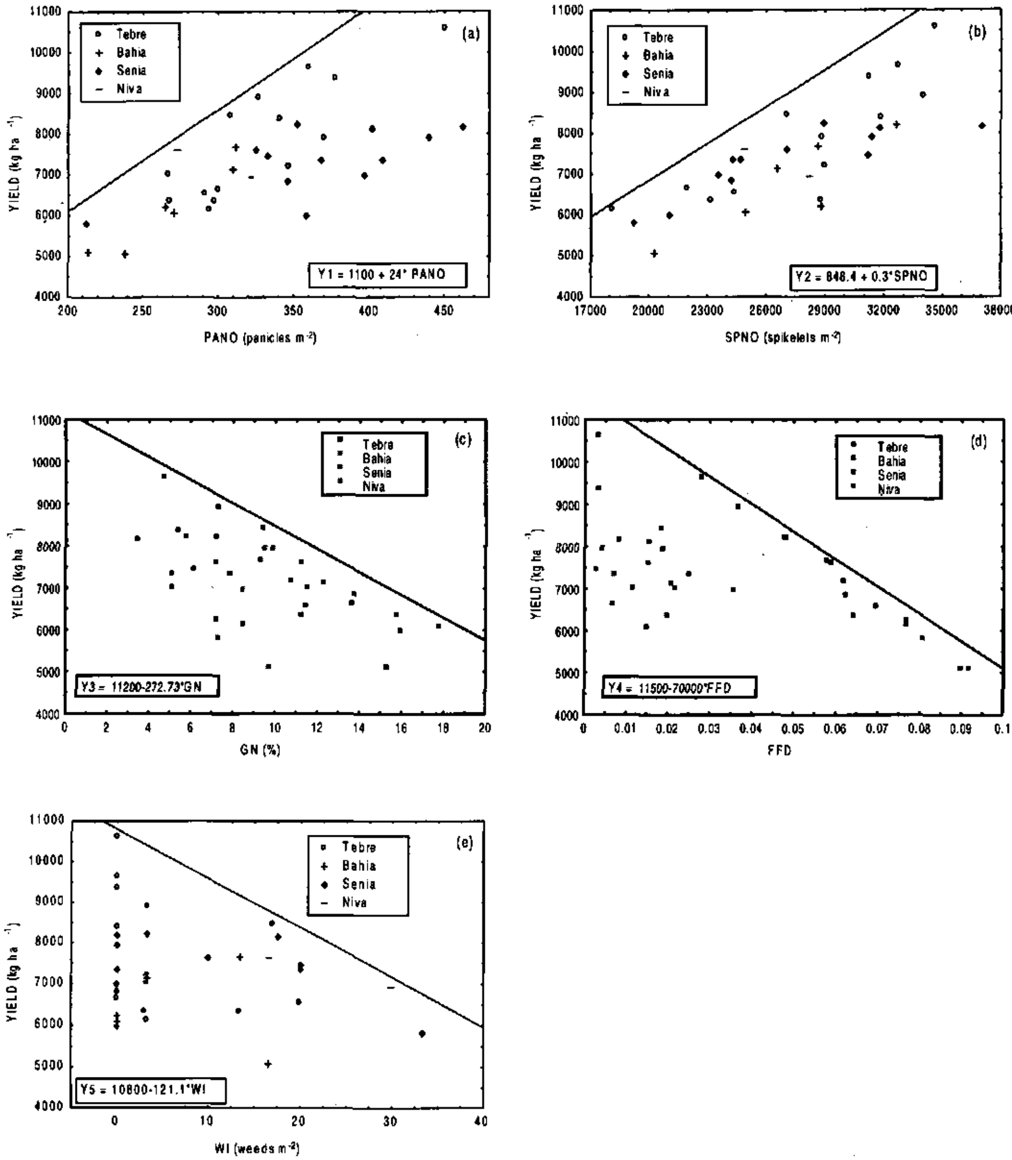


Fig. 7.4. Measured values in 1995 of yield for various cultivars (Bahia, Senia, Tebre and Niva) and yield components together with various adverse factors; **a**-PANO (panicles m^{-2}), **b**-SPNO (spikelet m^{-2}), **c**-GN (percentage of grains with necrosis), **d**-FFD (heterogeneity; standard deviation in f_{PAR} at flowering) and **e**-WI (weed infestation; weeds m^{-2} at ripening). The straight lines represent the maximum fitted lines.

components. Labels in Fig. 7.5 indicate the main source of yield limitation. However, this information should be handled with caution. In nature, plant characteristics are interrelated and reduced crop growth results from several interrelated factors simultaneously, e.g. a reduced number of grains together with that of panicles and perhaps also with high necrosis in grains. Thus, the occurrence of one of these five plant characteristics as a limiting factor, does not exclude the possibility that another plant characteristic is very close to limiting as well.

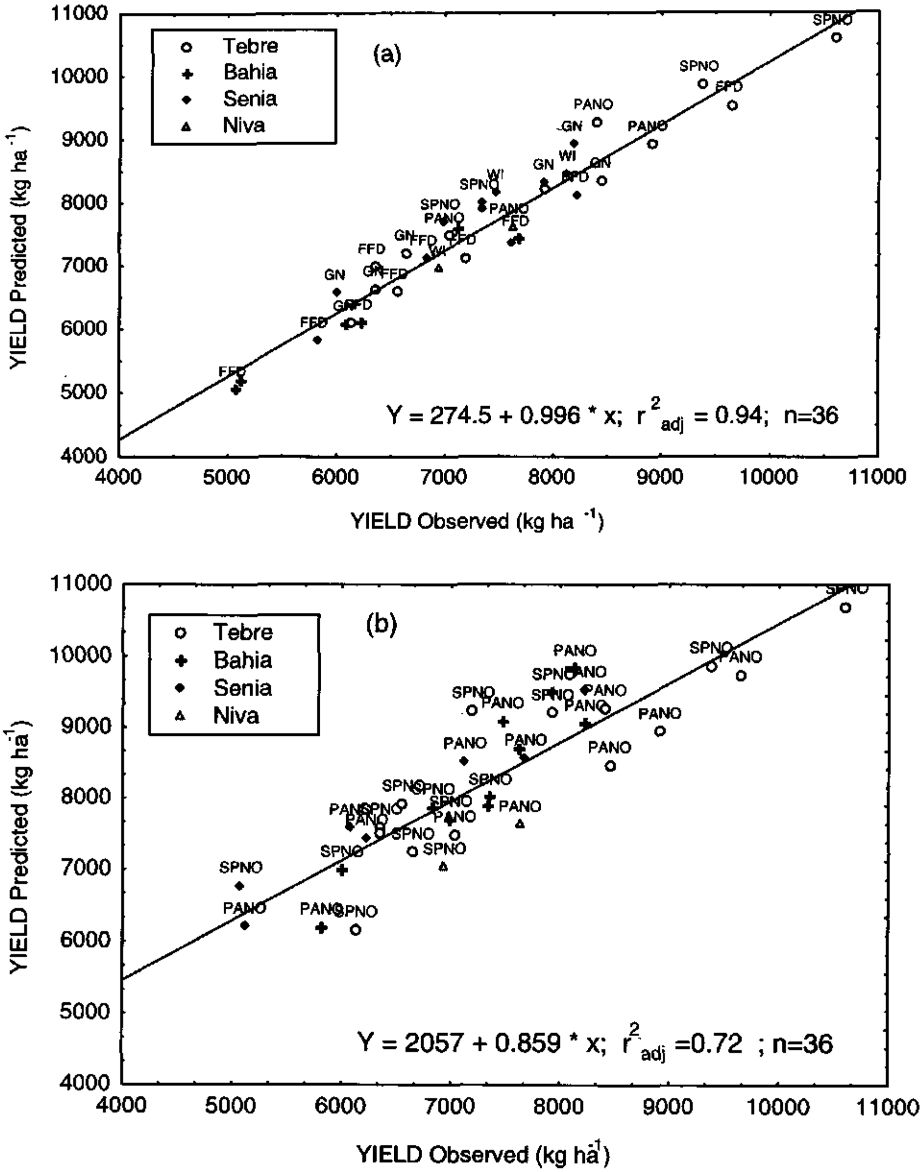


Fig. 7.5. Comparison of observed and predicted yield in 1995 from the model of equation 7.2 using **(a)** five variables (two yield componets and three adverse factors) and **(b)** two variables (just the two yield components). Labels indicate the main limiting variable; PANO (panicles m^{-2}), SPNO (spikelets m^{-2}), GN (percentage of grains with necrosis), FFD (heterogeneity; standard deviation in f_{PAR} at flowering) and WI (weed infestation; weeds m^{-2} at ripening). The line represents the regression equation.

7.3.2. Deducting significant variables of cropping status from yield components and some adverse factors (Step 2a).

When several variables are involved, the study of suitably calculated correlation coefficients may provide important clues to the underlying causal mechanism. Partial correlation coefficients were calculated and tested between the significant yield components and adverse factors of Step 1 and variables related to the cropping status. Significant correlations, at the $\alpha = 0.05$ level, between variables are marked in Table 7.1 with a positive or a negative sign depending on the type of correlation. Spikelets per unit area (SPNO) was split in the number of panicles per unit area (PANO) and the number of spikelets per panicle (SPP). SPP, contrary to PANO and SPNO, had a high scatter and no positive relation with yield. Table 7.1 showed that four main groups of causes were inhibiting rice growth:

(i) Potassium (K) was positively related to yield components (PANO, SPP and SPNO) and negatively to the adverse factors (GN, WI, FFD). The potassium content in the stems was a better indicator for diagnosis, probably because less than 20% of the absorbed potassium is translocated to the panicles (Yoshida, 1981). A strong positive interaction appeared between potassium content in the stems at maturity and spikelet number (Fig. 7.6a). K had the opposite effect to Na. Sodium content in the straw (but also in the grain) at maturity was negatively related to spikelet number as shown in Fig. 7.6b. Simultaneously, Fig. 7.6c shows the negative interaction between sodium and potassium content in the straw illustrating the antagonistic effect.

(ii) Zinc (Zn) content in the grains at maturity had a strong effect on the main plant characteristics as illustrated also in Fig. 7.7a,b. The zinc content in the grains was a better indicator for diagnosis, probably because up to 50 % of the Zn absorbed by a rice crop is in the panicle (Yoshida and Tanaka, 1969). Specifically a strong effect of low Zn levels on the fraction of grains with necrosis, therefore on the quality of the grains, and panicle number was found. Figure 7.7c illustrates how Zn also showed antagonistic effects to Na.

(iii) The number of plants available is related to various factors that determine yield. Low and heterogeneous germination values were recorded within farmers' fields. Data on plants and spikelets per unit area measured in the study area are shown in Fig. 7.8. Additional data of long-grain cultivars were incorporated. Figure 7.8 illustrates that above a threshold value of approximately 160-180 plants m^{-2}, the grain number stayed constant.

(iv) The length of the growing period and especially the pre-heading period had significant effects on the final yield, in particular on the grain number per unit area.

Other factors such as the N level in the grain at maturity and the N and P level in the leaves at tillering had separate and weak effects, so that we could not give a strong physiological basis for them.

Table 7.1. Significant correlation coefficients (at the α=0.05 level) of yield components and some adverse factors with variables related to the cropping status.Yield components: PANO (panicles m^{-2}), SPP (spikelets $panicle^{-1}$), SPNO (spikelets m^{-2}). Adverse factors: GN (fraction of grains with necrosis), WI (weeds m^{-2} at ripening) and FFD (heterogeneity, the standard deviation of PAR absorbed at flowering).

		PANO	SPP	SPNO	GN	WI	FFD
	Germination (%)	+.42				–.40	
	Plant_number	+.42				–.37	
	CVof plants	–.43			+.46		
	Length of vegetative st.						
	Length of pre-heading st.			+.43			–.43
	Length of post-heading st.						
	Length total			+.37			
Tillering	N_leaves						–.39
	K_leaves						
	P_leaves					+.41	–.37
	Na_stems						
	Zn_stems						
	K_stems						
	Mg_stems						
Maturity	Na_straw						
	Zn_straw	+.51	–.38				
	N_straw						
	K_straw			+.44			
	P_straw						
	Ca_straw						
	Mg_straw						
	Na_grain	–.42					+.41
	Zn_grain	+.41		+.45	–.39		
	N_grain		+.41				
	P_grain						
	Mg_grain						
	K_grain						
	Puddling before sowing						+.37
	Top-dressing fert.					-.45	

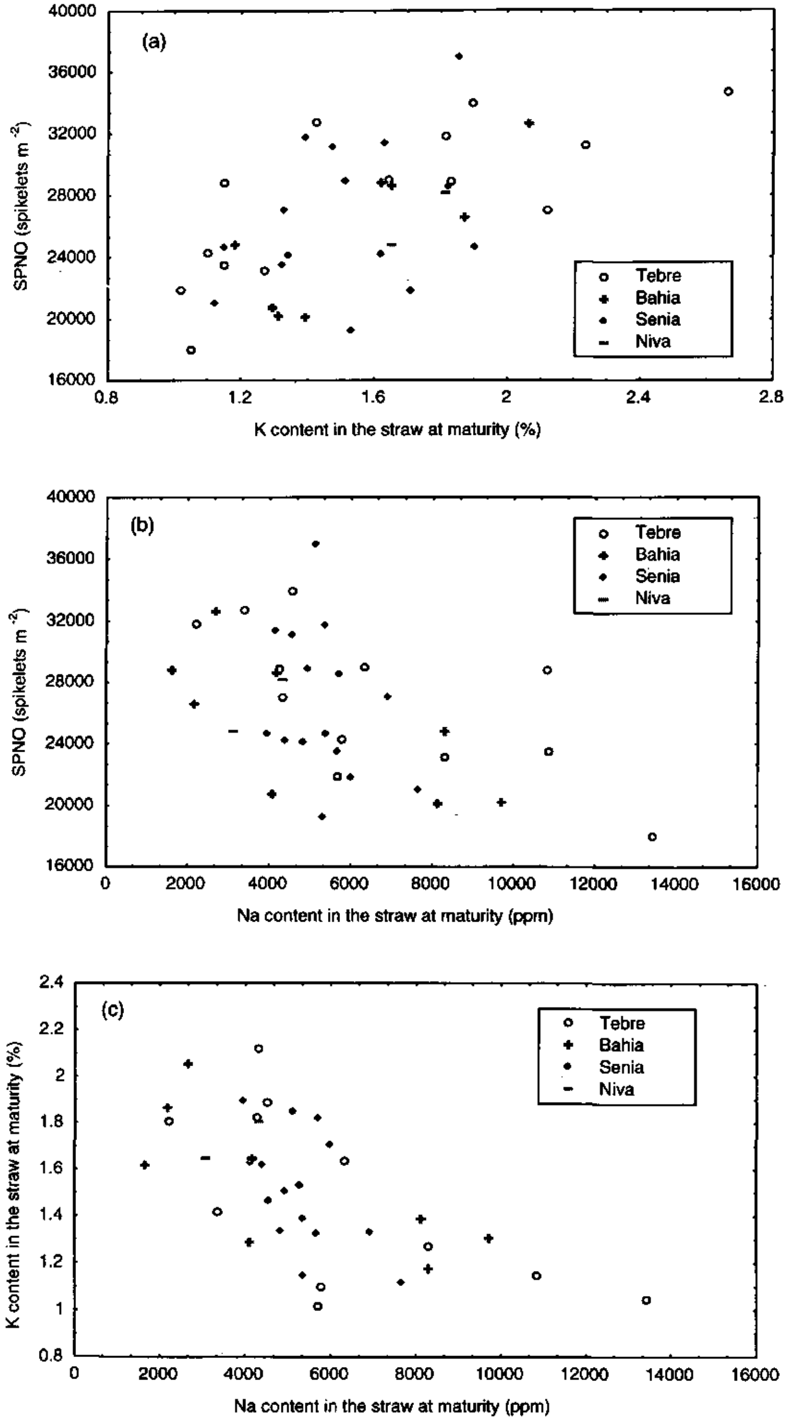


Fig. 7.6. Spikelet number relation to **(a)** K and **(b)** Na content in the straw at maturity. **Fig. 7.6c** shows the strong antagonism between K and Na content in the straw at maturity.

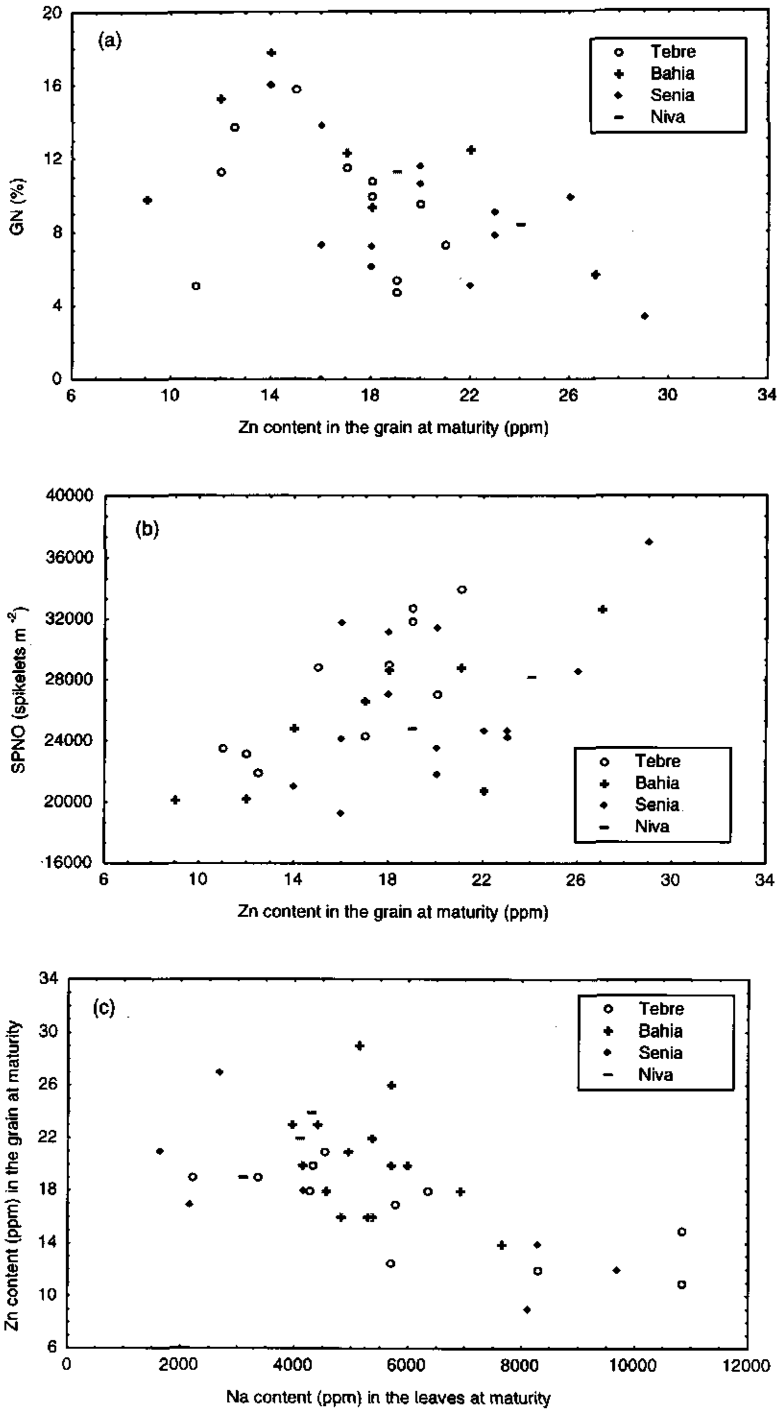


Fig. 7.7. (a) Percentage of grains with necrosis (GN) and **(b)** spikelet number (SPNO), against Zn content at maturity in the grain. **Fig. 7.7c** shows the strong antagonism between Zn and Na content at maturity in the plant.

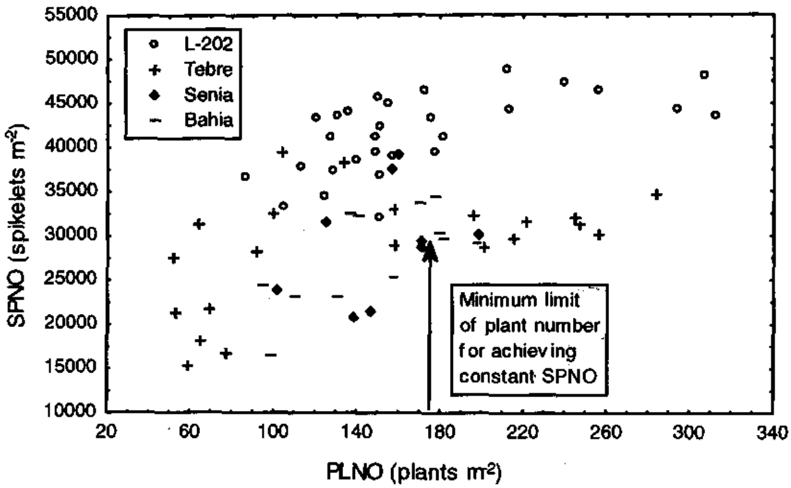


Fig. 7.8. Spikelet number against plants per unit area for a long-grain cultivar (L-202) and various round-grain cultivars (Tebre, Bahia and Senia) in 1995 and 1996.

7.3.3. Deducting significant variables of cropping status directly from yield values (Step 2b).

The law of the minimum of the limiting factors ("Min-Max" method) was used to relate directly yield values to the cropping status. The relation of various variables that quantify the cropping status with yield is shown in Fig. 7.9. The model of Eq. 7.2 was used for predicting yield from all the variables related to cropping status as explained in the Material and Methods Section. For every field, "N" fictitious yields were derived and the minimum of all was chosen. To identify the limiting factors in all the cases, finally, six variables were considered. These are:

K/Na_{ms} = ratio of K(%) to Na(ppm) at maturity in the straw,
Zn_{mg} = zinc content (ppm) at maturity in the grain,
N_{mg} = nitrogen (%) at maturity in the grain.
PLNO = plants per unit area (plants m^{-2}),
LT = length of the total growing period (days),
L_PreH = length of the pre-heading period (days),

These results are in accordance to the ones obtained in Step (2a). Based on these six variables and the model of Eq. 7.2, yield was predicted as shown in Fig. 7.10a. The slope is significantly different from 1 at the α=0.05 probability level but not at the α=0.01. The intercept is significantly different from 0 at both probability levels. Using three independent variables, as shown in Fig. 7.10b, the adjusted regression coefficient is similar to the one in Fig. 7.10a, but the intercept and slope are both significantly different from 0 and 1 respectively even at the α=0.01 probability level.

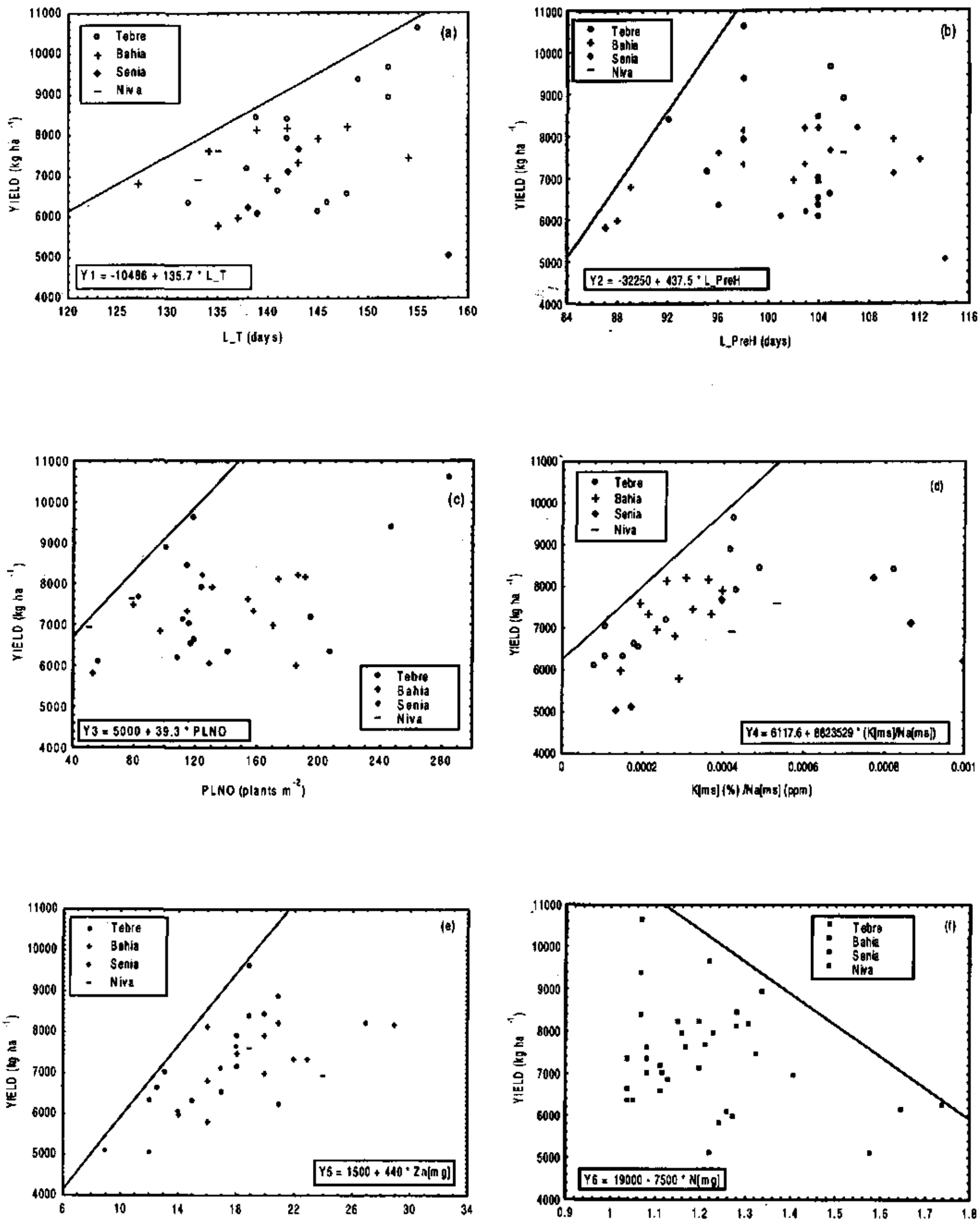
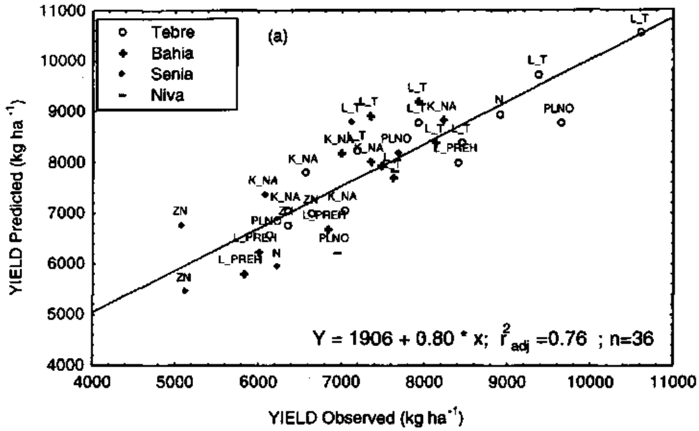


Fig. 7.9. Scatter plots of yield and variables related to the cropping status; **a**-L_T (length of the growing cycle), **b**-L_PreH (length of the pre-heading period), **c**-PLNO (plant number per square meter), **d**-K_{ms}/Na_{ms} (potassium to sodium ratio at maturity in the straw), **e**-Zn_{mg} (zinc content at maturity in the grain) and **f**-N_{mg} (nitrogen content at maturity in the grain). The straight lines represent the maximum fitted lines.



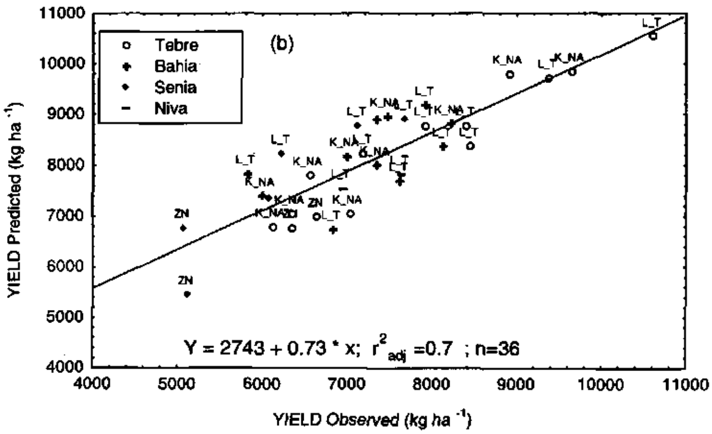


Fig. 7.10. Comparison of observed and predicted yield from **(a)** six and **(b)** three variables related to the cropping status using the model of Eq. 7.2. Labels indicate the main limiting source; L_T (length of the growing period), L_PreH (length of the pre-heading period), PLNO (plants per unit area), K_Na (potassium to sodium ratio at maturity in the straw), Zn (zinc at maturity in the grain) and N (nitrogen at maturity in the grain). The line represents the regression equation.

7.3.4. Deducting significant soil properties from the cropping status (Step 3)

Partial correlation coefficients were calculated and tested between the main variables of cropping status derived in Steps 2(a,b), and all measured soil properties. Significant correlations at the α=0.05 probability level among soil properties and the plant status variables, are shown in Table 7.2 with a positive or a negative sign depending on the type of correlation. Note that drainage status did not have any significant effects. The main soil properties that have significant effects on rice growth were grouped as:

(i) Soil salinity (measured in various forms) had negative effects on the potassium and zinc level of the plant. Figure 7.11a shows potassium content in the straw at maturity against soil salinity (of the saturated paste averaged for the top 100 cm). The K exchangeable in the soil was grouped in four classes and the exact values are indicated as labels. Figure 7.11a illustrates that with high soil salinity, the K content in the straw was low even when high values of K exchangeable are measured in the soil. This result indicates that in soils with high soil salinity, K absorption is hampered and low levels of K in the plant are reached that reduce growth. Figure 7.11b shows how Zn was negatively related to soil salinity, although not as strong as K. Zn content in the soil was not measured.

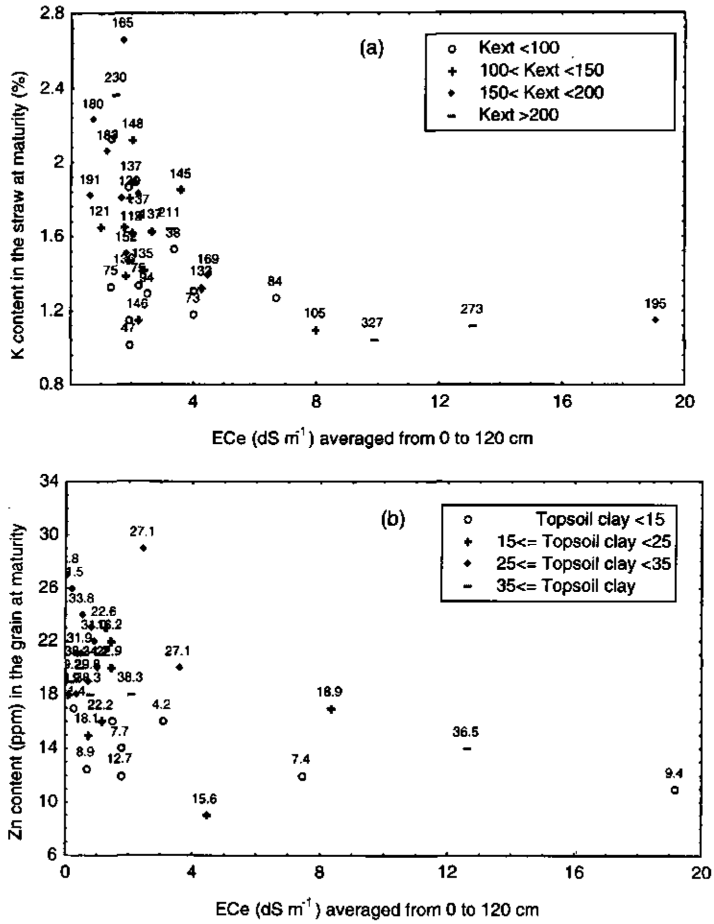


Fig. 7.11. (a) Potassium content at maturity in the straw against soil salinity (electrical condutivity of the saturated paste averaged in the profile down to 120 cm). Labels indicate the K exchangeable in the soil. Symbols distinguish classes of K exchangeable. Note that with high soil salinity, the K content in the straw was low even with high values of K in the soil. **(b)** Zinc content at maturity in the grain against soil salinity (electrical conductivity of the saturated paste averaged in the profile down to 120 cm). Labels indicate clay percentage of the topsoil. Symbols distinguish classes of clay fraction of the topsoil.

Table 7.2. Significant correlation coefficients (at the α=0.05 level) of the variables related to the cropping status with the soil properties. Soil properties: Development of structure is assigned with 1 while non-development with 0. Drainage class is ranked from well drained (1) to very poorly drained (9). Textural family is assigned with 1 if coarse and with 0 if non-coarse. EC1 is the soil salinity averaged from 0 to 120 cm before sowing. EC2 is the topsoil salinity before sowing. EC3 is the topsoil salinity at the panicle initiation stage. The rest of soil properties are easily identifiable.

	Germina -tion(%)	Plant number	CV of plants	Length Pre-heading	Length Total	Tillering N(leaves)	Maturity Na(straw)	Maturity Zn(straw)	Maturity K(straw)	Maturity N(straw)	Maturity Na(grains)	Maturity Zn(grains)	Maturity N(grains)
Development of structure													
Drainage class													
Textural family coarse							+.52		–.40		+.50	–.43	–.35
Clay(%) at 40-60 cm		+.36	–.54	+.51			–.42		+.36		–.40	+.43	
Clay(%) at 80-100 cm													
EC1 (dS m^{-1})							+.61	–.39	–.51			–.53	
EC2 (dS m^{-1})		+.35					+.66	–.51	–.47			–.55	
EC3 (dS m^{-1})	+.40	+.40					+.62		–.40	+.37			
Topsoil CEC (meq $100g^{-1}$)			–.45		+.37	+.37		+.48	+.37		–.39	+.40	
Topsoil pH								+.55	+.37	–.50		+.40	
Topsoil Clay(%)			–.45		+.36	+.41		+.59	+.45		–.35	+.50	
Topsoil Sand(%)			+.38		–.37	–.39	+.38	–.56	–.37		+.52	–.53	
Topsoil Silt(%)							–.39	+.49			–.56	+.49	
Topsoil SOM(%)			–.42										
Topsoil P (ppm)					+.37		–.35						
Topsoil K (ppm)	+.36		–.51										
Topsoil Mg (meq $100g^{-1}$)			–.44			+.43							
Topsoil N(%)			–.47										

(ii) The soil organic matter, N, K and Mg exchangeable, as well as the clay percentage and CEC of the topsoil had positive effects on the homogeneity of plants per unit area.

(iii) The clay and silt percentage, and the CEC of the topsoil, in addition, had positive effects on the Zn and K content of the plant, and the length of the growing period. It is unclear if this effect is direct through soil fertility or indirect by a relation with other soil properties. Figure 7.12 illustrates how low clay fraction in the topsoil induced Zn shortages. Zn absorption, furthermore, in topsoils with high clay fraction was reduced by a high soil salinity.

(iv) pH had positive effects on the Zn and K content of the plant.

(v) Favourable N levels in the plant were promoted by low salinity, high pH, and fine texture.

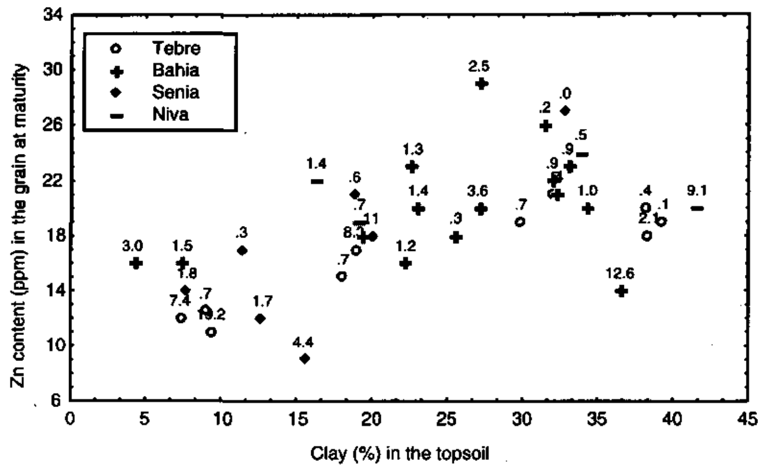


Fig. 7.12. Zinc content at maturity in the grains for various cultivars (Bahia, Tebre, Senia and Niva) against clay (%) of the toposil. Labels indicate soil salinity (electrical conductivity of the saturated paste averaged in the profile down to 120 cm).

7.4. DISCUSSION

The data provide a basis for understanding the processes of rice yield determination. When an inductive approach if followed, biophysical processes are considered and used to derive conclusions. Here, we followed a deductive process in which there is a risk of deriving relations that are not really causal. Thus, we should be extremely careful in extrapolating found relations.

Yield values were predicted with high accuracy from yield components and some adverse factors ($r^2_{adj} = 0.94$), and to a lesser extent from the variables related to the cropping status ($r^2_{adj} = 0.76$). This is due to the increase in causal distance between yield and the considered variables as shown in Fig. 7.2. Based on this reasoning, predicting yield from soil properties would give a lower regression coefficient. Such results were found in Chapter 6 and have been reported by other authors (Bouman, 1994; Greenwood et al., 1986; Ribeiro et al., 1984).

7.4.1. Deducting significant yield components and some adverse factors (Step 1)

Panicle number and spikelet number, as yield components, were expected to be significantly related to yield. In fact, they form the sink capacity of the rice plant. It is commonly accepted that it is impossible to have high yields if not enough spikelets are present. The weight of the grains can be measured as the weight of 1000 filled grains (GW_f) or of 1000 grains ($Gw_n = Gw_f \times$ fraction of filled spikelets). Here, we measured GW_f which had a small variability and was poorly related to yield.

Adverse factors came out significant. In fact, these adverse factors should have been avoided with an improved data collection. Intensity of weeds infestation and spatial heterogeneity, presumably, should have been reflected in panicle number on a 5.0 m^2 frame instead of a 0.5 m^2. Grains with necrosis was a particular case because the fraction of non-filled grains did not come out significant, showing the data a high scatter with yield. The scatter plot of yield and percentage of grains with necrosis in Fig. 7.4c, however, showed that a quick "rule-of-thumb" of yield estimate can be given at ripening stage, 2-3 weeks before harvesting. The percentage of grains with necrosis is related to the "quality" of the grains. Intensity of weeds infestation if high, had a strong effect on yield. This result is not important for rice physiology. From the point of view of rice agronomy in the study area, however, it shows that weeds are still a problem and are not always fully controlled.

7.4.2. Deducting significant variables of cropping status (Step 2)

Table 7.1 showed significant correlations between the yield components (and some adverse factors) and cropping status. The effects of cropping status were not directly linked to yield, but instead their effects were split up for various plant characteristics. Step (2b) which related directly yield to cropping status could be considered a validation of the methodology used in Step 1 and (2a). The results showed that the significant variables coming out were similar and, therefore, the methodology followed was correct. The various nutrient concentrations measured at maturity were more highly correlated with the yield components and adverse factors than those measured at tillering. This effect, presumably, was caused by the progressive dilution (deficiency) or concentration (toxicity) of the nutrients during the growing cycle. Five main groups of factors seem to be related to poor rice growth:

(i) *K shortage*. A low K content in the plant, induced by high sodium content, reduced significantly the panicle and spikelet number. High sodium levels were also associated with heterogeneity within the fields. Results shown in Fig. 7.6 show the antagonistic effect of potassium and sodium. A K/Na ratio represents this relation in the dataset (Fig. 7.9d). A low K/Na ratio in the plant straw at maturity may be used indirectly as a first estimate of a low production. Other authors (Qadar, 1995; Girdhar, 1988) reported that if high sodium levels exist in the plant, the potassium levels are low. According to Yoshida (1981), the critical value for potassium is 1.0%. In our dataset, the average K at tillering in the leaf blades was 2.2% with a standard deviation of 0.3%. The average K at maturity in the straw was 1.5% with a standard deviation of 0.4%. These values were apparently above the critical limits of Yoshida (1981). Yet, the scatter plots in Fig. 7.6 show that for our farm management conditions and soil units, the saturation level of potassium was not reached. Presumably potassium deficiency may be induced by sodium toxicity. This is in accordance with Khan et al., (1992b) and Bohra et al., (1995).

(ii) *Zn shortage*. Low Zn content in the grains at maturity was associated with panicle and spikelet number, and also with necrosis in grains. On one hand, this was a surprising result because Zn fertilization is uncommon in the study area and Zn deficiency was not expected. On the other hand, once discovered it is logical. Zinc deficiency of lowland rice has been widely reported in submerged soils (Patrick et al., 1985; Khan et al., 1992a,b; Beyrouty et al., 1994; Sharif Zia et al., 1994). Concentration of Zn in the soil solution generally decreases following flooding because of precipitation as $ZnCO_3$, $ZnSO_4$, or $Zn(OH)_2$ (De Datta, 1981). It is well known that this was the case in Pant Nagar in Uttar Pradesh, India (Yoshida and Tanaka, 1969). According to these authors, critical Zn contents in the shoot are 15-20 ppm. In the dataset, the average Zn content in the shoot at tillering was 31.5, but at maturity only 22.3 with 7 out of 38 values below 20. These low values of Zn together with its relation to yield components and adverse factors (shown in Fig. 7.7) induced a major inhibition of rice growth by Zn shortage.

(iii) *Low plant number per unit area*. A sufficient plant number is important for having enough panicles, but also for reducing weed infestation. Not only plant number but also its homogeneity within a field, had significant effects on weed infestation and on the fraction of grains with necrosis. Low and heterogeneous germination values were recorded within farmers' fields. Source-sink interrelationships are still poorly understood in physiological and agronomic rice studies. How the plant regulates the partitioning of nutrients among the spikelets still remains to be determined (Iwasaki et al., 1992; Dingkuhn et al., 1991b). Charles-Edwards (1984) discussed the supply of assimilates during grain filling in relation to the number of reproductive parts of a plant. The fact that the fraction of filled grains was on average 86% with only two values below 80% also indicates that there was not an excess of spikelets (Horie et al., 1997). Data shown in Fig. 7.8, as well as Fig. 7.9c, illustrate that a threshold value of 160-180 plants m^{-2} should be reached. These are indications that sink limitation is commonly found. Farmers sow between 500-600 seeds m^{-2} and low germination percentages may occur if low temperatures or strong winds are present. Stands are difficult to restore with reseeding because the oxygen concentrations in the soil and water are very low by the time a reseeding decision is made (Hill et al., 1991).

(iv) *Temperature*. The length of the growing period, and especially the pre-heading period, had significant effects on yield and the number of available spikelets per unit area. Rice under temperate climate is grown in summer time under high solar radiation. According to Angus et al. (1993), with full radiation commonly available, temperatures are indirectly limiting rice production either by its effects on spikelet sterility or on development rate. Our results are in accordance with Dingkuhn et al. (1991b), who showed that biomass at maturity was a function of crop duration.

(v) *High nitrogen content in the grains at maturity*, according to us, was a symptom rather than a cause. It indicated that something else limited growth, and as a result there was a surplus of N.

f_{PAR} values at flowering stage did not have significant effects on yield. This result indicates that in the study area, there is a sufficient maximum absorbed f_{PAR} or, in other words, of a sufficient maximum leaf area index (LAI_m). A field may have areas with low and high f_{PAR} simultaneously, as the results indicated with the deviation of f_{PAR} at flowering, but in most cases the average LAI_m was enough. It is a matter of homogeneity or the uneven growth within a field. Also note that variables such as the height of the rice plant at ripening and the deviation of f_{PAR} from the optimal at tillering, did not have a significant influence. The fact that the effect of f_{PAR} values at tillering and at flowering was not significant illustrates that most of the fields started well or without showing a strong difference that determined future yield. These results are in accordance with Ramasamy et al. (1997), who showed that most differences in rice growth due to soil properties are not clear before flowering and mainly show up in the period from flowering to maturity.

7.4.3. Deducting significant soil properties (Step 3)

Within the cropping status variables, crop establishment and duration are largely influenced by farm management, weather conditions and even nutrient status, besides soil properties. On the contrary, nutrient status is more directly related to soil properties. Figures 7.11 and 7.12 illustrate the relation of soil properties to the nutrient status. Soil submergence causes a substantial decrease in zinc concentration in the soil solution. Obermueller and Mikkelsen (1974) and Jugsujinda and Patrick (1977) found that increased tissue concentrations and uptake of Zn occurred with rice grown under aerobic conditions. After prolonged submergence, the zinc concentration declines towards a lower limit. According to Forno et al. (1975), bicarbonate and carbonate have inhibitory effects on zinc absorption in alkaline soils. In this study, zinc deficiency was not associated with high pH (extract 1:2.5 had a mean of 7.94 and a standard deviation of 0.16). In this area, it is mostly associated with poor soil fertility (low clay and silt content) and soil salinity. Both, Zn and K, were adversely affected by soil salinity as shown in Fig. 7.11a,b. These results indicate that in soils with high soil salinity, K and Zn absorption was hampered and only low levels of these cations were reached in the plant. In the case of K, high K in the soil did not help to increase the level of K in the plant. In the case of Zn, no data was available. Khan et al., (1992a,b), found that application of zinc improves the growth, yield and nutrition of rice even at the highest (16 dS m^{-1}) salinity level. Further research in Zn assimilation and interaction with other cations under submerged conditions is necessary. Topsoil clay and silt content, in addition, improved the levels of Zn and K, crop duration and plant establishment homogeneity.

7.5. CONCLUSIONS

The following conclusions can be drawn based on monitoring of rice growth and measurement of soil properties at various farms in the Ebro Delta (Spain):

(1) The source capacity, measured as the fraction of intercepted photosynthetically active radiation at tillering and at flowering, rarely limited rice growth. Rather, the sink capacity, in terms of available panicles and spikelets, was often a limiting factor.

(2) In addition to the panicle and spikelet number, adverse factors such as the fraction of grains with necrosis (quality of the grains), the intensity of weed infestation and the spatial heterogeneity within fields were needed to quantify yield at field level.

(3) Rice growth was limited strongly by potassium and zinc shortage. In both cases, a strong antagonism with sodium was observed.

(4) A minimum number of 160-180 plants m^{-2} was necessary to stabilize the spikelet number and, additionally, to reduce spatial heterogeneity and weed infestation.

(5) Final yield was a function of the length of the growing season. Especially the length of the pre-heading period, when the potential size of the crop is primarily determined, was of key importance.

(6) Potassium and zinc shortages in the plant were mainly induced by excess sodium. High sodium levels in the plant were caused by soil salinity.

(7) High levels of exchangeable K in saline soils did not increase K uptake. It remains to be determined if addition of Zn increases Zn uptake in the saline soils of the study area.

(8) High soil pH was not the cause of zinc shortage. In fact, pH was positively related to Zn content in the plant.

(9) Long growing cycle, homogeneity of plants per unit area, and adequate potassium and zinc levels in the plant were favoured by high clay contents of the topsoil.

7.6. ACKNOWLEDGMENTS

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General dicussion

8.1. THE LAND-USE SYSTEM OF THE EBRO DELTA

The major part of the Ebro Delta is, at present, under rice cultivation. The reason for this monocultivation is:

(i) The presence of saline groundwater over large areas near the soil surface. Rice is not tolerant to salinity (as shown in this research), but a continuous flow of ample amounts of irrigation water prevents capillary rise of saline groundwater.

(ii) Market factors. Council regulation (No 3072/95) of the European Commission provided an intervention price of approx. 300 ECU per tonne during the 1994-2000 period. This price is more than twice as much as that for other cereals such as wheat or barley! Furthermore in the last four years, prices of Japonica-type rice exceeded the intervention purchase price. This was not the case for Indica-type rice due to strong competition from imports.

(iii) Environmental policies. The European Commission published in May 1995 a communication on the wise use and conservation of wetlands. Regulation 1765/92 stressed that non-rotational crops can be beneficial and should be encouraged around protected wetlands. The implementation of the NATURA 2000 network and the Ramsar Convention, where the Ebro Delta was designated as one of the international renowned wetlands, establishes strategies and subsidies for stimulating agricultural production compatible with the protection of the environment and with the conservation of natural resources.

Yield potential in the Ebro Delta is 13000 kg ha^{-1}. At present the average actual yield is only 50% of this potential production and yields in the area are extremely variable, although the farming system is highly mechanized and the most up-to-date technology is used. Thus, still much effort needs to be done for improving rice production.

8.2. ENVIRONMENTAL AND AGRONOMIC CHARACTERISTICS

Main characteristics in relation to rice cultivation in the Ebro Delta have been discussed in this thesis, but they have to be considered in a broader context which still deserves attention:

(1) Soils.

• Soil levelling improves the efficiency of irrigation and drainage management, and the maintenance of a uniform water depth that facilitates establishment. High, unflooded parts of the field are notorious for rapid weed growth; low areas collect water and reduce seedling survival. Increasingly, rectangular areas of even slope are being constructed using laser-directed landforming equipment. This is a good development.

• Soil nutrients. N-P-K fertilization is common in the Ebro Delta, but practices can be fine-tuned to local conditions.

- This research has shown that nitrogen is not a limiting factor of rice growth in the Ebro Delta. This does not mean that nitrogen fertilization is optimal and nitrogen losses are minimum. It just means that nitrogen content in the plant, in general, is higher than the minimally required content. This author believes, together with other rice researchers such as Tabacchi of the Centro Ricerche sul Riso in Italy, that nitrogen effects on crop appearance, specifically on the greenness of the plant, are clearly visible to farmers. Thus, under an intensive rice cultivation, nitrogen shortages are rarely found because farmers tend to over-fertilize to avoid an unattractive appearance. An effort should be made to convince farmers that an optimal fertilization still produces a good color, while adverse environmental effects are avoided.
- Potassium shortages were recorded in various fields, but were mainly induced by soil salinity. A strong antagonism with sodium was observed. Other authors (Qadar 1995; Girdhar, 1988) had already reported that if high sodium levels exist in the plant, the potassium levels are low. Furthermore, high K exchangeable in saline soils did not increase K uptake. This means that more sophisticated actions such as artificial drainage to control soil salinity would be necessary.
- One interesting finding of this research has been a significant correlation between zinc content in the plant and yield from a selected subset of farms (Chapter 7). This means that zinc shortage induced a major inhibition of rice growth. This effect was expressed mainly in the quality of the grains. Deficiency of Zn, induced by the effects of submergence on carbonate and sulphide concentrations has been widely reported. In our research, deficiency of Zn was associated with poor soil fertility (low clay and silt content), soil salinity, but not with high pH. Literature (Matsuo et al., 1995) indicates Akagare Type II physiological disorder is caused due to Zn deficiency. It was reported as Khira disease in Uttar Pradesh (India) already back in 1964. Preflood or early postflood application of Zn is used in California (USA). In New South Wales (Australia), it is generally applied after landforming of the heavy cut areas, or where pH is more than 6.5 at a rate of 5-10 kg ha^{-1} zinc (Williams, personal communication). In Japan, shortage of zinc is not frequently reported. In South and Southeast Asia, however, the use of zinc fertilizers in paddy fields is becoming popular. Dr. Oda from the National Institute of Agro-Environmental Sciences (Tsukuba, Japan, unpublished data) found in 1996 a 20% yield increase in Kyushu paddy lands by using fertilizers

containing micro-nutrients (Zn and others). Nowadays, Zn additions are being introduced in the Ebro Delta as well as in the Camargue (personal communication, Roux-Cuvelier, Centre Français du Riz) and in the Po Valley (personal communication, Tabacchi). This research supports the fact that this is a good development.

• Poor drainage conditions were found in large areas of the Ebro Delta, as shown in Chapter 3. Chapter 6 showed that poor drainage conditions and a high/shallow groundwater table, did however not have negative effects on rice growth. It was the "quality" of the groundwater what was important. In the Ebro Delta, groundwater with a high salinity as evidenced by a high electrical conductivity reduced crop growth significantly. However, it was not the shallow groundwater by itself as reported by other authors, (e.g. Ramasamy et al., 1997). According to our results, harmful effects in terms of disturbance of the correct physiological balance and root oxidising power came mainly from the high sodium chloride content in the groundwater. Under healthy conditions, rice-leaves absorb oxygen that is transported through the stems to the roots creating an oxidized zone in the topsoil, rhizosphere, independently of the drainage status of the whole soil profile.

(2) Weather. Chapter 4 discusses the potential production of the Ebro Delta based on temperature and radiation.

• Radiation. Rice growth under a temperate climate, with long days and clear skies, is not commonly limited by radiation (Hill et al., 1991). In the Ebro Delta, the rice crop has on average a 130-150 days length of growing period. The potential yield of rice is determined between panicle initiation and flowering, while the post-heading period determines the ultimate yield. Data from our experimentation and of other rice growing areas in temperate climates such as Japan (Kobayashi, personal communication) and Australia (Williams, personal communication) have shown that:

$$\text{Yield (14\% moisture)} = 1.5 \times X \qquad \text{(Eq. 8.1)}$$

where X is the growth of above-ground biomass between panicle initiation and flowering (kg ha^{-1}). In places with radiation-limitations, such as the wet season in monsoon Asia, the amount of radiation during the post-flowering stage determines the fraction of filled spikelets and therefore yield. In summary, increasing the length of the reproductive pre-heading period or the number of spikelets would increase the production in Spain but not in Philippines or in India during the wet season. This also addresses the importance of having a leaf area index (LAI) at panicle initiation (PI) that corresponds to full cover or, to a minimum of 3 m^2 leaf m^{-2} soil, as shown in Chapter 4. At flowering, maximum LAI between 5.5 and 6.5 should be reached. Such type of data should be communicated to plant breeders and biotechnologists.

• Cold temperatures. At least temperatures of 10 to 12 °C are required for germination, thus preventing early sowing. These temperatures occur from the 10th of April onward in the Ebro Delta and from 20th of April onward in the Camargue and Po-valley. Late sowing is limited because an adequate temperature is needed at flowering and also because of the risk of strong storms in late September or October. Flowering requires minimum temperatures between 18 and 22 °C, depending on the cultivars. The Ebro Delta has a smaller thermal constraint than the Camargue (France) and the Po valley (Italy). This means that there is still some margin for growing longer-cycle cultivars, that would have a higher yield potential with respect to the other two major rice growing areas in Europe. This is because of its lower latitude and proximity to the sea compared with the other two major sites. Interior-lands have a higher diurnal temperature fluctuation with a lower night temperature. Cold-induced sterility is not commonly recorded in the Ebro Delta contrary to the other two mentioned sites. This, however, does not exclude an effect of temperature in development rate, photosynthesis and leaf area extension growth. The particular advantages of the Ebro Delta should be explored by developing adapted cultivars which sustain high and stable grain yield and quality.

• Wind. Strong winds that blow down the Ebro Valley in the Ebro Delta (Cierzo or "Vent de dalt") or in the Rhone Valley in the Camargue (Mistral) are frequent. They can create problems at early rice development, by covering the seeds with a layer of soil, or at late ripening stages by lodging the crop.

- Large parcels are preferred in terms of farm management. At early rice growth, however, these strong winds are the main limitation to parcel size, because of the damage to young rice seedlings in large open water expanses (Hill et al., 1991). Trees could be grown around the fields but various inconveniences emerge: (i) cutwinds have a limited zone of influence because of the flatness of the area, (ii) trees have shadowing effects and favour birds nesting, and (iii) tall tress obstruct farm management, especially aircraft work.
- At late maturity stages these inland dry winds, if not too strong, are favourable for drying of the grains and reducing pests infestation. They can have, however, a negative effect on the quality of the grains (percentage of full grains from the mill) if they are very dry and accompanied by calm but humid nights (Mouret, 1988). Further research is necessary to understand better the effects caused by climate and farm management in the ripening process for improving the quality of the grain yield.

• Storms. As mentioned above, very intense and short storms are common in the Mediterranean basin in September and October. These, if accompanied by wind, can lodge the crop which terminates grain growth and hampers the harvest of rice grains. An additional problem of rice lodging in comparison to other cereals is that rice fields are commonly still flooded when storms occur. This means that often the grains, ready to be harvested, get submerged in the water and are lost due to rotting. So, as mentioned in the next point, differences in water management can avoid such problems. Water management, however, depends on the land concept.

(3) Water management.

- From seeding to tillering under the water-seeding method, the farmers dry the fields one or more times but with certain caution because of conflicting objectives: (i) On the one hand the drying of the fields facilitates the germination of the seeds by oxygenating the soil surface. Drying improves the anchorage of the rooting system of the plant, reduces the development of algae and fungi, and is necessary to reduce losses in the top-dressing fertilization and application of chemical herbicides. (ii) On the other hand, the role of the water layer as a thermal buffer (during cold temperatures and strong winds) is lost, as well as its salinity control effect. So when climate inconveniences emerge or in highly saline soils, flooding conditions can reduce the negative effects of temperature and salinity on the number and homogeneity of plants per units area. Nowadays, however, the dry seeding method (Chapter 2), which requires to incorporate the seed into the soil, is applied in some parts, especially in non-saline soils and small "risky" farms.
- From flowering to harvesting, water management is also controversial: (i) in some places, e.g. the Ebro Delta, the continuous flow of irrigation water is maintained until the very end (for maintaining the plant "alive"!), (ii) in other places, e.g. the Po-valley, irrigation stops shortly after flowering (for improving the ripening of the grains and reducing fungi infestation!). In the USA, some farmers have begun to employ new recirculating irrigation systems and automated shutoff valves that conserved up to two-thirds of the water requirements of 30 years ago (http:\\www.usarice.com). The design of schemes reducing water use deserves further consideration in the area.

(4) The production system.

• Seedling emergence. In the Ebro Delta, as in other temperate rice growing regions, seedling emergence is complicated. The water-seeding method as described in Chapter 2 is the most commonly used in the Ebro Delta. Low and heterogeneous germination values do occur within farmers' fields. A threshold value of approximately 160-180 plants m^{-2} was found necessary to maximize yield in Chapter 7. To reach these values, farmers sow between 500 and 600 seeds m^{-2}, irrespective of soil properties. Water management and soil properties, however, were found to be crucial properties for determining seedling germination. Thus, in our opinion farmers, extension workers and rice scientists in general, should start thinking and talking in terms of established *plants per unit area*, rather than on seeding rate. Seeding rate does not give any information on the results of an experiment or on a rice field! The number of plants per unit area is a starting-point, only, from which later developments can be derived.

• Length of the growing period. On the one hand, short-cycle cultivars are preferred for avoiding risks because of the thermal constraint. On the other hand, long-cycle cultivars are preferred because of their higher yield potential. The length of the growing period was found to be similar among typical cultivars (Tebre, Bahia, Senia and L-202) grown in the Ebro Delta at present time. Short and long-grain cultivars, however, had differences in the length of the pre-heading and post-heading period which gave differences in crop characteristics (as shown in Chapter 4). Future breeding programmes should exploit this diversity in farming preferences, and especially even more with the present trend to improve quality and diversify rice grains.

• Source-sink relationships. Various rice fields were monitored in 1994-1996. Main differences appeared from flowering to maturity. From seeding to flowering, if a good seedling was achieved, no major differences were found. The high tillering capacity of the cultivars compensated other effects, and rarely differences in weight or LAI before flowering were found (so that a source limitation was rarely recorded). During the post-heading period, however, a yield gap emerged between potential and actual yields. Differences in yield arise from differences in sink capacities. This was inferred from the observation that the fraction of filled grains was high (on average 86.7%) and that frequent stem growth occurred at late stages. Our results showed that high yields were correlated with a high number of spikelets (35000 and 47000 spikelets m^{-2} for short and long-grain cultivars, respectively) and with healthy and alive plants until harvest.

• The rate of leaf photosynthesis is determined by leaf characteristics and environmental factors. At three sites with differences in soil conditions (such as soil salinity and topsoil clay), leaf assimilation was measured during the post-heading period in 1994. For crop simulation purposes, the well-known photosynthesis light response curve (Fig. 8.1) of individual leaves can be characterized by the (i) initial light use efficiency and (ii) maximum rate of leaf photosynthesis. The initial light use efficiency (initial slope of Fig. 8.1) is calculated based on a linear relation with temperature (Ehleringer and Pearcy, 1983) who observed similar values between C3 species. The light saturated rate of leaf CO_2 assimilation (asymptote of Fig. 8.1) within species varies, depending on temperature and nitrogen concentration.

At low light, a shortage of RudP will presumably limit the CO_2 assimilation. At high light intensities, on the other hand, there is enough RudP but diffusion of CO_2 from the outside of the leaf to the chloroplasts (within the mesophyll cells) will limit assimilation. This is the most common in rice grown under clear skies, except for the lower leaves where a certain radiation limitation may exist. Fig. 8.2 shows the relation between CO_2 assimilation and CO_2 difference. The difference in CO_2 is a consequence of assimilation rate. At high assimilation, a large difference results. This figure shows that the stomata will close at low assimilation (the slope of the line connecting an observational point with the origin indicates the stomatal conductance). The important point for discussion, however, was the large degree of scattering in the data that did not allow to uncover differences due to soil conditions in the three sites. In addition to leaf assimilation, of course it was the total LAI that determined canopy assimilation as well. Further detailed research at various sites and development stages, however, would be necessary to really uncover how differences in rice yield, due to soil conditions, are caused by a photosynthesis limitation at leaf level or by a limitation in absorbed radiation at the plant level or by a difference in the fraction of the grains with necrosis or by another parameter.

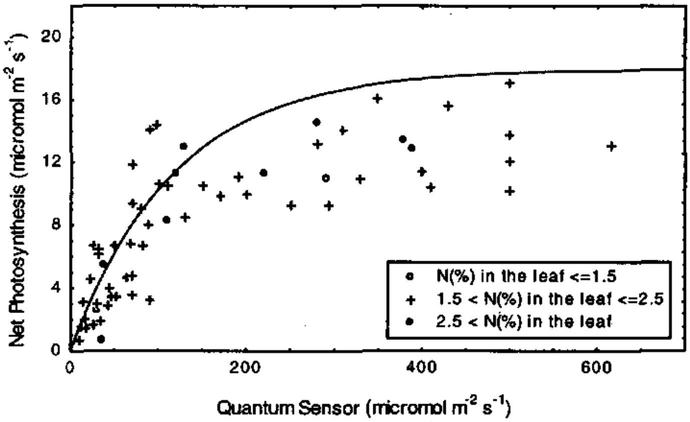

Fig. 8.1. Net photosynthesis (micromol m^{-2} s^{-1}) against PAR (micromol m^{-2} s^{-1}) for cultivar Tebre in 1994 at various N level in the leaves (unpublished data). The line represents the negative exponential curve with common values of initial slope and asymptote for C_3 crops.

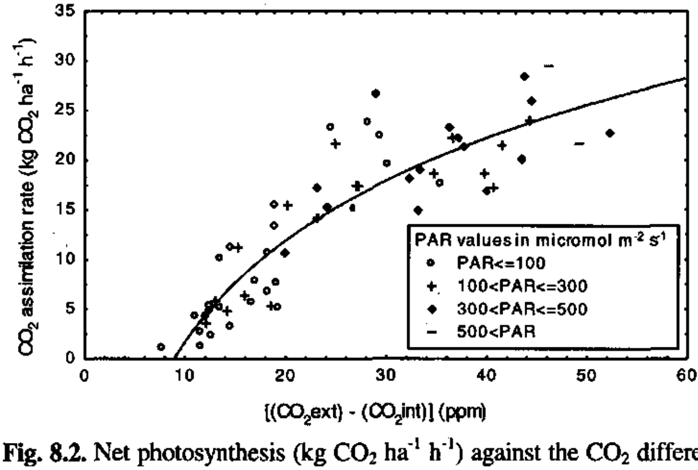

Fig. 8.2. Net photosynthesis (kg CO_2 ha^{-1} h^{-1}) against the CO_2 difference between the outside and the mesophyll concentration for leaves of cultivar Tebre in 1994 (unpublished data) at various PAR levels. The line represents the adjusted logarithm fit.

• The conversion coefficient for intercepted PAR into total aboveground dry matter diminished slightly at the late stages of development (see Fig. 5.6), but an effectively constant value of 2.25 g MJ^{-1} was applied from seeding to maturity. This value is equal to 1.1 g MJ^{-1} for radiation-conversion efficiency (intercepted global radiation instead of intercepted PAR). Our results are in good accordance with Horie et al. (1997) results in Australia, where he found values of radiation-conversion efficiency of 1.1, instead of 1.4 as in Japan. For the value of the radiation-conversion efficiency in Japan, the estimated yield potential at the Ebro Delta is 16 t ha^{-1}. This we consider unrealistically high, and the discussion shows the importance of defining clear physiological conditions when discussing potential production.

(5) High costs of production. This is a common problem in agriculture of the so-called developed countries. The EC agricultural policy (CAP), which was intended to make the EC self-sufficient in agricultural production, has resulted in very high costs and a trade imbalance (Bond, 1994; Mookhoek et al., 1992). At present, profitability is the main objective.

(6) Lack of crop rotation. For rice monoculture, the high costs of production are "two-times true". A cropping system with alternate crops would reduce presence of weeds, fungi, and other management practices. Bacteria such as *Sclerotium spp.* incubate under submerged soils. Special mention deserves the wild-rice or "crodo" as it is called in Italy. It is also rice, *Oryza sativa,* which grows a bit advanced with respect to the domesticated rice. The inconvenience of wild rice is that the grains fall easily from the panicle and further on, they have a reddish colour. The wild rice is very difficult to eliminate because it belongs to the same species as the normal rice (Kwon et al., 1992). According to our observation and Tabacchi and Roux-Cuvelier (personal communication), weed infestation is a major problem in direct-seeded rice in Europe. Transplanted rice allows a better weed control, but is not operational where labour costs are high. This year-after-year direct-seeded rice growth increases production costs and further on reduces yield.

(7) World Trade Organization agreements. The deficit of Indica rice in Europe inspired the Commission of the European Communities to allocate subsidies for long-grain rice from 1988 to 1992. Since 1993, after the last GATT agreement, no direct subsidies are allowed for areas planted with long-grain rice. In a few years, it will be relatively easy to import rice at the intervention price of the world market. This means that a kilogram of rice will be easily purchased at half of the present European price. Taking into account that the rice production of Spain is mainly consumed within the same country, at present it seems reasonable to keep the traditional round and medium-grain cultivars, which are locally preferred.

(8) Environmental pressure. Until the EC Hill Farming Directive from 1986, the farmers' lack of enthusiasm to combine the needs of agriculture and the environment posed a significant impediment to government policy. Since then, environmental factors have increasingly been taken into account within agricultural production. The Ebro Delta, as well as the Camargue and the Guadalquivir marshes, are aquatic environments that are nowadays regulated by its corresponding Natural Park management offices. They apply firm protective measures for nature conservation of the wetlands. Fortunately or unfortunately, the rice production system has to take into account this interrelation with nature conservation. New instruments aimed at reducing this tension are to be developed such as management and maintenance agreements. However, the financial repercussions of management agreements and nature reserves will be considerable, and high costs may seriously restrict the feasibility of the policies of land management.

8.3. FUTURE RESEARCH NEEDS

(1) Suggestions for soil science.

• At present, the concept of soil geographic databases for soil cartography is important, rather than "static" paper maps (King and Le Bas, 1996). This is even more important in such a flat deltaic area with high textural and taxonomic variability. Future research, however, is necessary for assessing tools that allow the design of integrated schemes with interaction and positive feedback among procedures of data collection-analysis-presentation.

• Future research should be oriented towards developing operational decision support systems for improving decision making at farm level based on soil and climate data.

• Rice-soil interactions. An operationalization of Von Liebig's law was developed in Chapters 6 and 7 where the limiting factors for rice production were estimated at the upper envelope of the datapoints. These limiting factors could result from cropping status or soil conditions. Lower accuracy in yield prediction was obtained from the soil factors because of a longer distance in the causal chain from seeding to harvest. This method, however, deserves further consideration because of its simplicity and accuracy.

• There is a need for incorporating available soil data, such as topsoil cation exchange capacity, into lowland-rice growth models under fully irrigated conditions to demonstrate why the plant acts differently in different types of soil. If soil data are not enough, pedotransfer functions may be derived, but always after knowledge on the natural processes is available. Until now, this author is not aware of any lowland rice process-based models which relate soil properties to rice growth.

(2) Suggestions for crop modelling.

• A good simulation of (i) development and (ii) LAI is essential. A model can have a very accurate dry matter assimilation module, but if development and LAI are not properly simulated, the dry matter production will not be properly simulated as well.

(i) Various models of crop development have been reported (Gao et al., 1992; Yin, 1996). These models use phenological events such as flowering and maturity stage as input data. At present, it is relatively easy to find data on seeding, flowering and harvesting date in research stations and universities. Harvesting date, however, is not the same as maturity stage. At locations with two or three growing cycles per year, one may harvest as soon as possible to allow land preparation for next season. Other places which use big machinery, such as combines, need to wait for harvest until 19-23% moisture. A clear and universal definition of maturity stage for all crop modellers remains to be determined. This issue was also stressed at the GCTE-WCRP Workshop (START, 1997).

(ii) At present in most "SUCROS-based" models, LAI simulation is very sensitive to the growth rate of the leaf area during exponential growth and is merely carbohydrate-dependent after full cover is achieved.

- The effect of temperature on relative growth during the exponential phase (RGRL) is considered constant in the actual version of ORYZA1 v1.3. Fig. 4.6 showed, however, that RGRL diminished with temperature sum. Because of its strong sensitivity when simulating leaf area (and therefore crop growth), further research is necessary to quantify these early processes of leaf area growth. This author proposes as a simple alternative a linear functionality of RGRL with temperature-sum as is done in other crop models such as SIMRIW (Horie et al., 1992) during this early stage.
- The expression that LAI simulation is carbohydrate-dependent means that after the exponential phase, LAI is derived directly from multiplying the weight of the green leaves by the specific leaf area (SLA). Other models simulate LAI from nitrogen content (TRYM; Williams et al., 1994), from temperature sum (SIMRIW; Horie et al., 1992), or from a combination of carbohydrate dependence and nitrogen (APSIM; McCown et al., 1996). Values of SLA measured in 1995 and 1996 (shown in Fig. 4.7) illustrated differences between years. This result together with evidence that LAI is also a function of nitrogen, lead to an important question as to the stability of SLA as a crop characteristic.

• The simulation of death or loss of the leaves is calculated, at present time, using a relative death-rate of leaf weight. From Fig. 4.4 it can be observed that, the increase in dead leaves is similar to the increase in green leaves after a 50-days delay. Simulation of the death of leaves needs attention and can be simplified.

• The calibrated and validated ORYZA1 model for Mediterranean conditions can at present simulate rice growth accurately until flowering. After flowering, however, divergences appear and increase specially after the milky dough stage. The main sources of error may be caused by a limited understanding of the ripening, maintenance and sink-limitation processes. ORYZA1 is a source-dependent crop growth model. Sink-dependent modules need to be introduced in order to better understand the plant interrelationships. The tillering module is still weak. Grain number is determined from growth between PI and flowering, which is a cultivar-specific characteristic. In nature, however, plant-spacing plays an important role in tillering. Much effort is still to be made in the improvement of simulating the development of tillers, florets and grains, as well as grain filling in rice.

• Attention to cultivars is necessary, but an "operationalization" of crop modelling requires a grouping of cultivars.

(3) Use of remote sensing. Field-based predictions had practical applications, especially for biomass estimation which was predicted from spectral reflectance with a higher accuracy than LAI. In addition, the continuously flooded rice fields offer the advantage that standard reflectance values can be applied to different soil types. Several authors (e.g. Foody and Curran, 1994) have shown that thanks to further development remote sensing and GIS techniques have become unique tools at the regional level. Further research is necessary to integrate the study of rice reflectance at field level at a higher hierarchical level.

(4) Rice adaptation and grain quality. Breeding programmes are to be created for the development of improved rice cultivars of various grain and market types to sustain high and stable grain yield and quality with minimum environmental impact in Europe. Emphasis is to be placed on rice grain quality; especially on high milling yield, cooking characteristics, kernel size, shape and translucency (lack of pearl). This characteristics improve marketability of rice.

(5) Sustainability. Rice growers, extension workers, nature conservation groups, and government agencies should co-operate to provide an optimum utilization of the land resources for improvement of the Ebro Delta rice productivity and profitability while enhancing the environment. This thesis was committed to conducting and supporting rice improvement research to help meet these goals.

Summary

This thesis presents a quantitative analysis of fully irrigated direct-seeded rice cropping and its relation to soil and weather conditions in the Ebro Delta in Spain. The general objective is to understand the "rice-soil-weather" system in the study area. Why is rice monocultivation the major land-use of the area? How does rice grow and develop? What is the maximum production in the Ebro Delta? Which soil properties are limiting and how does this affect rice growth (e.g. do they induce a nitrogen or a zinc shortage or a ..., do they reduce the number or the weight of grains or ...)?

The general objective can be divided into the following specific objectives:

(1) To determine key soil properties and their distribution, to understand the soil-functioning processes, and to create a soil geographic database with these data.

(2) To determine the optimal growth curve for a rice crop based on weather (temperature and radiation) under no "soil-related" limitation. In technical terms, to assess the potential production growth curve.

(3) To determine the interrelation between soil properties and rice growth. The aim is to understand "which & how" soil properties are affecting rice growth. In simple words, identify *which* soil properties contribute to the yield-gap between potential and actual production. Understand *how* soil properties are affecting the crop status which at the end of the causal chain determines yield.

The Ebro Delta landscape, next to its flatness, is characterized by the vast extent of regularly laid out paddy fields. Given the present market factors and environmental policies, the main reason for the farmers to have rice in monocultivation is the presence of saline groundwater near the soil surface over large areas. Although rice is not tolerant to salinity, as shown in this research, the continuous flow of irrigation water needed to grow rice prevents the capillary rise of saline groundwater that would otherwise increase even more soil salinity. To supply and drain away these great quantities of irrigation water (on average 4000 liters of water are used per kg of paddy rice produced), a dense network of irrigation and drainage canals are required. A detailed description of the Ebro Delta environmental conditions (climate, water resources, geomorphology), socio-economic basis and rice production system is presented in Chapter 2.

Chapter 3 gives the answer to the first specific objective examining the soils, their spatial distribution and characteristics, on the northern part of the Ebro Delta (left bank). The soils were classified based on (i) soil development, (ii) soil texture, (iii) drainage status and (iv) soil salinity. In the areas where no soil development had occurred, its characteristics reflected variability of the parent material. The texture of

the sediments was related to the depositional environments and landforms: in the fluvial environment, as an example, a grading in the sediments diameter existed (from fine sand to clay) based on proximity to the discharge area. Storms and waves have acted by dispersing the sediments and flattening the topographic features. Drainage status was quantified and soil salinity measured, while their causes and distribution were analysed. The soil types (detailed in Fig. 3.3 and Table 3.4) can be grouped as:

- Soils non-developed with medium to fine textures, which are well drained and non-saline (NM1,2) or imperfectly drained and moderately saline (NM3,4,5). They are found in the banks of the actual or old river courses. Especially NM1,2-type soils allow crop rotation and are very valuable because of this flexibility. For rice cultivation, however, all of them lack a certain clay percentage in the topsoil.
- Soils non-developed with medium to fine textures, which are poorly to very poorly drained. They are found in the floodplain that is near the adjacent uplands (NM9), old river courses and lagoon basins (NM8) and transition zones (NM6,7). NM9-type soils are non-saline because the groundwater in that area is non-saline, due to its high elevation with respect to the rest of the Delta. NM6,7,8-type soils are highly saline reaching maximum values of the electrical conductivity in the saturated paste of 30 dS m^{-1}. (Taking into account that a soil with a value higher than 4 dS m^{-1} is considered saline; 30% of the cultivated area on the left bank of the Ebro Delta is above this threshold value!). The high salinity of NM6,7,8-type soils does not allow cultivation of any crop other than rice. In addition, it even reduces rice growth as shown in Chapters 6 and 7.
- Soils non-developed with coarse textures. They are found near the sea (NC5,7,9) and at the head of abandoned courses (NC3). These soils are sands with or even without a shallow layer of fluvial origin on top. Their drainage status depends on their proximity to the sea. NC5,7,9 are moderately saline because of the opposing effects of proximity to the sea and high leaching, while NC3 is non-saline. Their fertility is low, mainly due to their low clay and silt content. Nowadays, however, moderate yields of rice are recorded with appropriate technology such as 3 or 4 split fertilizer applications and good care for fungi.
- Developed soils, which are characterized by the presence of a calcium carbonate accumulation (DM3,4,5,7) or a histic horizon (DP9) within 100 cm depth. They are encountered near the continental shelf in a rather limited extension. They are the best soils for rice cultivation because of their high clay and silt content plus their low salinity, even though they have poor drainage conditions.

The survey methodology was innovative as it combined expert knowledge, grid survey and short-distance measurements. A soil geographic database (SGD) or geo-information system was created to store, analyse and present soil data. The SGD had many advantages with respect to a static "paper map", but especially the flexibility of the database management was of great value. Two methodologies were used to define the required terrain features:

(i) The "object-oriented" approach which assumes that terrain features can be defined with each having a geometric position and shape. Datasets with discrete terrain units containing soil type, textural-size class from the base of the slowly permeable layer (≈ 30 cm) to 100 cm depth, and epipedon texture (USDA) were created by means of this method. Limits were drawn based on refinement of the surveyor model by combining soil data and ortophotomaps.

(ii) The "field" approach which assumes terrain features to be continuous in space. Continuous datasets of elevation and various soil properties, relevant in the study area, were created by interpolation from soil data.

Differences within geomorphological units, and its specific effects on the soils, were better expressed with the object-oriented approach. Differences within a unit, of elevation and simple soil properties (such as salinity and drainage status) that change gradually, were better expressed in the "field" approach. The design of schemes a priori, that combine both approaches for collecting, analysing and presenting data is of great value for land-use systems analysis.

Chapter 4 provides the answer to the second specific objective and to other related questions such as, e.g. what are the rice land-use requirements? What are the cropping differences between a short-grain and a long-grain cultivar (without the effects of the soil)? Which are the optimum nitrogen levels in the plant? We have monitored under good soil and management conditions a short-grain cultivar (Tebre) and a long-grain cultivar (L-202), widely cultivated in the Ebro Delta. Potential rice production was established as a function of environmental conditions on which the farmer does not exert influence: temperature and radiation. The explanatory model ORYZA1 (Kropff et al., 1994) was used for simulating rice growth, development and leaf area index (LAI) under potential production. This study aimed at testing the performance of ORYZA1 for Mediterranean conditions. ORYZA1 was calibrated and validated mainly with field data from 1994-96. Phenological development of the rice crop, daily dry matter production and leaf area development were calibrated. Tebre and L-202 had no significant differences in overall development rate. The pre-heading period, however, was longer and the post-heading period shorter in L-202 than in Tebre. This induced differences in translocation, tillering capacity, weight of the grains and harvest index. The following crop characteristics were similar for the cultivars: light extinction coefficient (it increased from 0.35 to 0.61 with development stage), dynamic nitrogen distribution (optimal values of nitrogen in the leaves were 3.5% at panicle initiation and 2.5% at flowering stage), partitioning of assimilates, relative death rate of leaves, relative growth rate of leaf area during exponential growth (0.009 $(°Cd)^{-1}$ with a Tbase of 10 °C), specific leaf area (between 15 and 25 m^2 kg^{-1} dry matter of leaf) and a strongly decreasing specific stem green

area (between 2 and 20 m^2 kg^{-1} dry matter of stem). Under optimal growth conditions, values of 450 and 600 panicles m^{-2} for Tebre and L-202 were reached respectively. Best simulation results were achieved when considering that the LAI represents leaf blade area only, with no contribution of stem green area to the photosynthesis apparatus of the rice plant. The model simulated rice growth very accurately until flowering. After flowering, however, divergences appeared and increased especially at the yellow ripe stage. From then on the crop did not grow much more, whereas it continued to do so in the simulation. This reduction of growth rate was usually accompanied by an increase in relative death rate of leaves and drying of the grains. The main source of error may be a limited understanding of the ripening and sink limitation processes. A considerable yield-gap (2000 kg ha^{-1}) between potential and maximum actual yield remained. A climatic variability assessment over the last ten years showed a small, but similar variation (coefficient of correlation 0.7) in simulated and measured rice yields.
Individual farmers may want to know their rice crop status for optimum management. In agriculture, monitoring of crop growth, development and, early estimates of final yield are of great interest. Consequently, Chapter 5 deals with the estimation of rice biomass and LAI by monitoring reflectance at field level with a hand-held radiometer. First, vegetation indices (RVI, NDVI, WDVI, PVI) were calculated from rice crop reflectance. The fraction of intercepted photosynthetically active radiation (PAR), f_{PAR}, was calculated based on a physical reflectance model from the vegetation indices. WDVI and PVI, indices that correct for soil reflectance, showed a more linear and less scattered relation than NDVI and RVI. The NDVI relationship with f_{PAR}, gave a good prediction during the vegetative period but saturated at $f_{PAR} \geq 0.4$. The soil reflectance needed for PVI and WDVI could be easily standardized for continuously flooded fields (10.2% = red reflectance; 7.0% = near-infrared reflectance). Two procedures are discussed: (i) estimation of LAI and (ii) estimation of biomass. The first procedure links f_{PAR} with LAI by means of the extinction coefficient (K) which varies during the growing season. The dynamic behavior of K was analysed and calibrated for different development stages. LAI was estimated directly from the calculated f_{PAR} once K was established. This procedure accounted for only 67% of the variance in LAI. The second procedure uses the Monteith model that requires one crop specific parameter, the conversion factor (α) for intercepted PAR into dry matter. Values of α for direct-seeded paddy rice were 2.25 g MJ^{-1} for aboveground (including dead leaves) biomass over the growing period, but were smaller towards the end. Estimation of biomass from remote sensing data appeared to be more reliable than estimation of LAI.

The answer to the third and last specific objective, or the final integration between rice and soil conditions is presented in Chapters 6 and 7. In Chapter 6, we identified and quantified the soil properties that limited rice growth, and in Chapter 7 what negative effects these soil properties, -together with farm management-, had on the cropping status. A total of 50 fields spread along the Ebro Delta were selected where all the environmental variables and their interrelations were evaluated at field level. On one hand, soil units were described and the main characteristics in the epipedon were measured. On the other hand, rice characteristics were measured during the growing cycle such as plants per unit area, nutritional status of the plants, length of the development periods, LAI at panicle initiation and at flowering, quantity of weeds and fungi, and yield components. A high variability in rice growth and final yield was observed!

Chapter 6 shows the most important soil properties for rice yield: (i) topsoil CEC, and clay and silt content; (ii) topsoil pH in the range of 6.9 to 7.9; (iii) soil salinity, which was negatively related with yield. Soil salinity was highly correlated with the electrical conductivity of the groundwater. The groundwater was found to be of marine origin, mixed in with fresh water and consequently with high differences in its electrical conductivity (from 2 to 60 dS m^{-1}). High groundwater tables did not have significant effects on rice yield, except when the water had a high salt content. Thus, the groundwater needs to be controlled only if highly saline. Several statistical and mathematical procedures were applied to compare rice yield among parcels. The simple correlation coefficient was used to make a pointwise comparison between yields and soil variables. Stepwise regression allowed prediction of yields from soil variables. The Law of the Minimum of the limiting factors, first proposed by Von Liebig, identified the part of the yield-gap (approx. 3000 kg ha^{-1}) due to soil properties. An unidentified yield-gap of 1000 kg ha^{-1} remained. Several other factors could also have effects, even though they did not emerge here. These statistical procedures do, however, not provide mechanistic explanations for the plant-soil processes. The usual effects of water limitation in rainfed agriculture under Mediterranean conditions are not present here and therefore, under flooding conditions, yield data for a particular year can be representative for other years. Thus, results obtained for 1995 can be used to suggest certain types of management in certain areas allowing a relatively high efficiency of natural resource use also in years for which no statistical analyses exist.

Chapter 7 aims to quantify rice growth at field level in relation to the cropping status and soil properties. Rice growth was monitored and soil properties were measured. Yield was related to soil properties by a deductive process identifying the yield determining factors. First (i) yield components, then (ii) variables related to cropping status and finally (iii) soil properties were identified. To interrelate the different groups of variables, correlation analysis and an operationalization methodology of the Law of the Minimum ("Min-Max" method) were used. To quantify yield at field level, besides panicle and spikelet number, the fraction of grains with necrosis (quality of the grains), the intensity of weed infestation and the spatial heterogeneity within fields were necessary factors. Accuracy of yield prediction for these five variables was very high (r^2_{adj} = 0.94). Four main groups of causes limited rice growth: (i) potassium shortage and (ii) zinc shortage where a strong antagonism of either factor with sodium was observed, (iii) poor plant establishment (as a minimum number of 160-180 plants m^{-2} was necessary to maximize yield), and (iv) length of the growing season, especially the length of the pre-heading period in which the potential size of the crop yield is primarily determined. The accuracy of yield prediction from these variables was moderately high (r^2_{adj} = 0.76). The larger the "causal distance" between yield and its determining factors, the lower the prediction accuracy. Potassium and zinc shortages in the plant were mainly induced by soil salinity. Zinc shortage was not more serious at high soil pH. High potassium in saline soils did not increase potassium uptake. It remains to be determined if addition of zinc increases zinc uptake in the saline soils of the study area. The length of the growing period was primarily determined by temperature, and also by soil properties. High clay content in the topsoil was a favourable factor for long growing cycle, better homogeneity of plants per unit area, and adequate potassium and zinc levels in the plant.

Chapter 8 is a general discussion of the project, extending its view to other rice growing areas in the temperate climate such as the Camargue (France), the Po valley (Italy) and the New South Wales riverine district (Australia). The purely agronomic characteristics in relation to rice cropping are discussed, -such as soils, weather, water and farm management-, as well as more socio-economic factors such as high costs of production, environmental pressure and WTO agreements. The effects of weather conditions on rice growth were quantified with an explanatory model. The effects of soil properties on rice growth were statistically treated. Thus, explanatory models for the effect of soil properties remain to be developed. This research has shown that easily available soil data can explain 75% of the yield gap. To really understand these differences processwise, further incorporation of soil data into lowland-rice growth models is necessary.

Research has shown that there is a big gap between what is potentially possible and what is achieved. We explored the "best-farmers" scenario. We compared and analysed yield differences between "good/bad farmers" and "good/bad soils". Some farmers do well, however, others don't! This thesis offers the potential to move beyond "just random experimental work". Future research should be oriented towards developing decision support systems for agricultural and environmental management at the major land units. *What* to do *when* is the major question. In what ways are soils functionally different? Future farmers and decision-makers should have the necessary tools for deciding themselves what to do based on a thorough knowledge of the area and its natural processes!

Samenvatting (summary in Dutch)

Dit proefschrift geeft een kwantitatieve analyse van de groei van volledig geïrrigeerde, rechtstreeks ingezaaide rijst in de Ebrodelta in Spanje, en de samenhang van de groei met bodem- en weersomstandigheden. De algemene doelstelling is om beter begrip te krijgen van het systeem van "rijst-bodem-weer" in het studiegebied. Waarom is monoculture van rijst het overwegende landgebruik in het gebied? Hoe groeit de rijst en ontwikkelt die zich? Wat is de maximum produktie in de Ebrodelta? Welke bodemeigenschappen zijn beperkend voor de groei van de rijst en hoe werkt de invloed ervan (bijvoorbeeld, veroorzaken zij een tekort aan stikstof of aan zink, reduceren zij het aantal korrels, of het gewicht van de korrels etc)?
De algemene doelstelling valt uiteen in de volgende deelvragen:

(1) Vaststelling van de kenmerkende eigenschappen van de bodem en van de verdeling daarvan, begrip van de bodemvormende processen, en vervaardiging van een geografische database voor deze gegevens.

(2) Bepaling van de optimale groeicurve voor een rijstgewas, alleen gebaseerd op klimaatsfaktoren (temperatuur en straling), dus geen bodemgerelateerde beperking. In technische termen, vaststelling van de groeicurve bij potentiële produktie.

(3) Bepaling van de samenhang tussen bodemeigenschappen en groei van de rijst. Het doel is te begrijpen welke bodemeigenschappen de groei van de rijst beïnvloeden en hoe ze dat doen. In eenvoudige termen, aangeven *welke* bodemeigenschappen bijdragen tot het verschil in opbrengst tussen potentiële en actuele productie. Begrijpen *hoe* bodemeigenschappen de toestand van het gewas beïnvloeden, die aan het eind van de causale keten de opbrengst bepaalt.

Het landschap van de Ebrodelta wordt gekarakteriseerd door een enorme uitgestrektheid van regelmatig aangelegde rijstvelden in een heel vlak gebied. Bij de huidige marktfactoren en milieubeleid is de belangrijkste reden voor de boeren om rijst in monoculture te verbouwen de aanwezigheid van zout grondwater vlakbij het bodemoppervlak. Hoewel, zoals in deze studie aangetoond, rijst niet tegen zout water bestand is, kan de continue stroom van irrigatiewater toch de capillaire opstijging van zout grondwater voorkomen, die anders de bodemverzilting nog zou verergeren. Voor aanvoer en drainage van deze grote hoeveelheden irrigatiewater (gemiddeld is 4000 liter water nodig om 1 kg rijstkorrels te produceren) is een dicht netwerk van irrigatie- en drainagekanalen nodig. Een gedetailleerde beschrijving van de omgevingsomstandigheden van de Ebrodelta (klimaat, waterbronnen, geomorfologie), de socio-economische basis en het rijst-productiesysteem is gegeven in Hoofdstuk 2.

Hoofdstuk 3 beantwoordt de eerste deelvraag door de bodems te onderzoeken op de noordelijke oever van de Ebrodelta (linkeroever), hun ruimtelijke verdeling en hun karakteristieken. De bodems werden ingedeeld op basis van (i) bodemontwikkeling, (ii) textuur, (iii) drainagestatus en (iv) bodemsaliniteit. In de gebieden waar geen bodemontwikkeling was opgetreden, waren de karakteristieken een weerspiegeling van het moedermateriaal. De textuur van de sedimenten werd gerelateerd aan de afzettingsomgeving en landschapsvormen: in de fluviatiele omgeving bijvoorbeeld kwam een gradiënt voor in de sedimentdiameter (van fijn zand naar klei) als functie van de nabijheid tot het uitstroomgebied. Stormen en golven hebben er toe bijgedragen om de sedimenten te verspreiden en de topografische kenmerken af te vlakken. De drainagetoestand werd gekwantificeerd en bodemsaliniteit gemeten, terwijl hun oorzaken en verdeling werden geanalyseerd. De bodemtypes (nader aangegeven in Tabel 3.4 en Figuur 3.3) kunnen worden gegroepeerd als:

- Bodems met een lemige textuur, goed gedraineerd en niet zout (NM1,2) of onvolledig gedraineerd en matig zout (NM3,4,5). Zij worden aangetroffen op de oevers van de huidige en vroegere rivierlopen. Vooral bij NM1,2 types is gewasrotatie mogelijk, en vanwege deze flexibiliteit zijn deze bodems heel waardevol. Voor de verbouw van rijst hebben ze echter alle een te laag kleigehalte in de toplaag.
- Slecht tot zeer slecht gedraineerde bodems met hoge gehaltes aan klei en silt. Zij worden gevonden in de overstromingsvlakte nabij de naburige heuvels (NM9), oude rivierlopen en lagunes (NM8) en overgangszones (NM6,7). NM9-type bodems zijn niet zout omdat door de hoge ligging in verhouding tot de rest van de delta het grondwater in dit gebied niet zout is. NM6,7,8-type bodems zijn heel zout, en bereiken maximum waardes van geleidbaarheid in de verzadigde pasta van 30 dS m^{-1} (een bodem met een waarde boven 4 dS m^{-1} wordt al als zout beschouwd; 30 % van het gecultiveerde gebied op de linkeroever van de Ebrodelta bevindt zich boven deze drempelwaarde). De hoge saliniteit van NM6,7,8-type bodems laat geen verbouw toe van andere gewassen dan rijst. Bovendien reduceert het zelfs nog de groei van rijst, zoals aangetoond in de Hoofdstukken 6 en 7.
- Bodems met grove structuur. Deze worden aangetroffen nabij de zee (NC5,7,9) en aan de kop van voormalige waterlopen (NC3). Deze bodems zijn zandig met of zonder een dunne toplaag van fluviatiele oorsprong. Hun drainagetoestand hangt af van hun nabijheid tot de zee. NC5,7,9 zijn matig zout vanwege de tegengestelde effecten van de nabijheid tot de zee en hoge doorlaatbaarheid,

terwijl NC3 niet zout is. Hun vruchtbaarheid is laag, voornamelijk vanwege hun lage klei- en siltgehalte. Tegenwoordig zijn echter redelijke opbrengsten mogelijk door toepassing van aangepaste technologie zoals een drie- tot viervoudig gedeelde bemesting en goede schimmelbestrijding.

Goed ontwikkelde bodems, gekarakteriseerd door de aanwezigheid van calciumcarbonaat (DM3,4,5,7) of een histische horizon (DP9) binnen 100 cm diepte. Zij worden aangetroffen nabij het oude land maar met een beperkte verbreiding. Zij zijn de beste bodems voor de verbouw van rijst, vanwege hun hoge klei- en siltgehalte alsmede hun lage saliniteit, dit ondanks hun slechte drainage-eigenschappen.

De karteringsmethodologie was innovatief door combinatie van expertkennis, rasterkartering en korte-afstandsmetingen. Een bodemgeografische database (BGD) of geo-informatiesysteem werd opgesteld om de bodemgegevens op te slaan, te analyseren en te presenteren. De BGD had veel voordelen vergeleken met een statische kaart op papier, maar vooral de flexibiliteit van de databasemanagement was heel waardevol. Twee methodologieën werden gebruikt om de benodigde terreinkenmerken te bepalen:

(i) De "object-geöriënteerde" benadering die er vanuit gaat dat er discrete terreineenheden kunnen worden bepaald met elk een geometrische positie en thematiek. Datasets met discrete terreineenheden werden door middel van deze methode opgebouwd, aan de hand van bodemtype, textuurgrootteklasse gerekend tussen de basis van de slecht doorlaatbare laag tot op 100 cm diepte, en textuur van de bovengrond (USDA). Begrenzingen werden getekend op basis van verfijning van het karteringsmodel, door combinatie van bodemgegevens en orthofotokaarten.

(ii) De "veld" benadering die ervan uit gaat dat terreinkenmerken continu in de ruimte verlopen. Continue datasets voor elevatie en voor verscheidene bodemeigenschappen van belang in het studiegebied, werden opgebouwd door interpolatie.

Verschillen binnen geomorfologische eenheden, en hun specifieke effecten op de bodems, konden beter tot uitdrukking worden gebracht door de object-geöriënteerde benadering. Verschillen binnen een eenheid in elevatie en in eenvoudige bodemeigenschappen (zoals saliniteit en drainagetoestand) die geleidelijk veranderen, konden beter tot uitdrukking worden gebracht door de "veld" benadering. Voor de analyse van landgebruiksystemen is het heel waardevol om schema's die beide benaderingen voor verzameling, analyse en weergave van gegevens combineren, van te voren op te stellen.

Hoofdstuk 4 gaat in op de tweede deelvraag en op andere daarmee verband houdende vragen zoals bijvoorbeeld die naar de vereisten voor een rijstgewas. Wat zijn de gewasverschillen tussen een cultivar met een korte en met een lange korrel (afgezien van de effekten van de bodem)? Wat zijn de optimale stikstofniveaus in de plant? Wij hebben een kortkorrel cultivar (Tebre) en een langkorrel cultivar (L202) die representatief zijn voor het studiegebied, onder optimale omstandigheden nauwkeurig gevolgd. De potentiële rijstproductie werd vastgesteld als functie van omgevingsomstandigheden waarop de boer geen invloed kan uitoefenen: temperatuur en straling. Het verklarende model ORYZA1 (Kropff et al., 1994) is gebruikt voor de simulatie van de groei van de rijst, de ontwikkeling en het bladoppervlakteindex (LAI) bij potentiële productie. Deze studie was gericht op het testen van de prestatie van ORYZA1 voor mediterrane omstandigheden. ORYZA1 werd voornamelijk met veldgegevens uit de jaren 1994 - 96 gecalibreerd en gevalideerd. Fenologische ontwikkeling van het rijstgewas, dagelijkse drogestofproductie en bladoppervlakteontwikkeling werden gecalibreerd. Tebre en L202 toonden geen significante verschillen in de totale ontwikkelingsnelheid, maar bij Tebre was de periode vóór het schieten langer en die na het schieten juist korter dan bij L202. Dit veroorzaakte verschillen in translocatie, uitstoeling, korrelgewicht en oogstindex. De volgende gewaskarakteristieken waren hetzelfde voor de cultivars: lichtuitdovingscoëfficiënt (nam gedurende de ontwikkeling toe van 0,35 tot 0,61), dynamiek van de stikstofverdeling (optimale waardes voor bladstikstof waren 3,5% bij pluimaanleg en 2,5% bij bloei), verdeling van assimilaten, relatieve sterftesnelheid van blad, relatieve groeisnelheid van bladoppervlak gedurende de exponentiële fase (0,009 $(^{\circ}Cd)^{-1}$ met een basistemperatuur van 10 °C), specifiek bladoppervlak (tussen 15 en 25 $m^2\ kg^{-1}$ droge stof aan blad) en een sterk afnemend specifiek groen stengeloppervlak (tussen 20 en 2 $m^2\ kg^{-1}$ droge stof aan stengel). Onder optimale omstandigheden werden waardes bereikt van 450 en 600 pluimen m^{-2} voor, respectievelijk, Tebre en L-202. De beste simulatieresultaten werden verkregen als werd aangenomen dat de LAI alleen bestaat uit bladschijf, zonder bijdrage van het groene stengeloppervlak aan het fotosynthetische apparaat van de rijstplant. Het model simuleerde de groei van rijst zeer nauwkeurig tot aan de bloei. Na de bloei ontstonden echter verschillen die vooral in het afrijpingsstadium groter werden. Vanaf dat moment groeide het gewas niet veel meer, terwijl het dat volgens de simulatie nog wel zou moeten doen. Deze afname van groeisnelheid werd gewoonlijk vergezeld door een toename van de relatieve sterftesnelheid van de bladeren en droger worden van de korrels. De voornaamste oorzaak van de fouten is waarschijnlijk dat we de processen van afrijping en vorming van opnamecapaciteit voor assimilaten nog slecht begrijpen. Een aanzienlijk opbrengstgat (2000 kg ha^{-1}) tussen potentiële en actuele maximum opbrengst bleef over. Een schatting van de effecten van klimaatvariabiliteit over de laatste tien jaar toonde een kleine, maar tamelijk gelijke variatie (correlatiecoëfficiënt 0,7) van gesimuleerde en waargenomen rijstopbrengsten.

Individuele boeren willen misschien de toestand van hun gewas weten voor optimaal management. In de landbouw is het van groot belang om de groei van het gewas en de ontwikkeling nauwkeurig te volgen en een vroege schatting van de uiteindelijke oogst te geven. Daarom gaat Hoofdstuk 5 over de schatting van de biomassa van rijst en van de LAI, en wel door middel van het volgen van de reflectie in het veld met behulp van een draagbare stralingsmeter. Eerst werden vegetatieïndices (RVI, NDVI, WDVI, PVI) berekend uit de reflectie door het rijstgewas. De fraktie onderschepte fotosynthetisch actieve straling (PAR) , f_{PAR}, werd berekend uit de vegetatieïndices op basis van een fysisch reflectiemodel. De indices WDVI en PVI die corrigeren voor bodemreflectie, gaven een meer lineaire relatie met minder spreiding dan NDVI en RVI. De relatie tussen f_{PAR} en NDVI gaf een goede voorspelling gedurende de vegetatieve periode maar toonde verzadiging bij f_{PAR} boven 0,4. De bodemreflectie die voor PVI en WDVI nodig was kon eenvoudig worden gestandaardiseerd voor continu bevloeide velden (10,2 % voor rood-reflectie en 7,0% voor nabij-infrarood-reflectie). Twee procedures worden besproken: (i) schatting van LAI en (ii) schatting van biomassa. De eerste procedure verbindt f_{PAR} met LAI door middel van de extinctiecoëfficiënt (K) die gedurende het groeiseizoen varieert. Het dynamische gedrag van K werd geanalyseerd en gecalibreerd voor verschillende ontwikkelingstadia. De LAI werd direkt geschat uit de berekende f_{PAR} zodra K vastgesteld was. Deze procedure verklaarde slechts 67% van de variantie in LAI. De tweede procedure gebruikt het Monteith model die één gewasspecifieke parameter nodig heeft, de conversiefaktor (α) voor onderschepte PAR naar droge stof. De waarde van α voor ingezaaide rijst was 2,25 g MJ^{-1} voor bovengrondse (inclusief dood blad) biomassa over de periode van volle groei, maar tegen het eind werd het wat lager. Schatting uit remote sensing gegevens van biomassa bleek wat nauwkeuriger dan schatting van LAI.

De beantwoording van de derde en laatste deelvraag, die naar de uiteindelijke integratie van rijst en bodemomstandigheden, is te vinden in de Hoofdstukken 6 en 7. In Hoofdstuk 6 werd vastgesteld welke bodemeigenschappen voor de groei van rijst beperkend waren en werden ze gekwantificeerd, en in Hoofdstuk 7 wat de negatieve effekten waren van deze bodemeigenschappen op de toestand van het gewas, in samenhang met de landbouwbedrijfsvoering. Een totaal van 50 akkers verspreid over de Ebrodelta werden uitgezocht waarvan alle omgevingsvariabelen en hun onderlinge relaties werden geëvalueerd op veldniveau. Aan de ene kant werden de bodemeenheden beschreven en de belangrijkste karakteristieken van het epipedon gemeten. Aan de andere kant werden de rijstkarakteristieken gedurende de groeicyclus gemeten zoals het aantal planten per grondoppervlak, voedingstekorten van de planten, duur van de ontwikkelingsperiodes, LAI bij aaraanleg en bij bloei, onkruiden, schimmels en oogstcomponenten. Er werd een grote variabiliteit in de groei van rijst en de uiteindelijke opbrengt gevonden!

De belangrijkste bodemeigenschappen voor de groei van de rijst waren: (i) CEC (kationenuitwisselingscapaciteit) van de toplaag en klei- en siltgehalte; (ii) pH variërend van 6,9 tot 7,9; (iii) bodemsaliniteit, die negatief gerelateerd was met de opbrengst. Bodemsaliniteit was sterk gecorreleerd met de elektrische geleidbaarheid van het grondwater. Gevonden werd dat het grondwater van mariene oorsprong is, ingemengd met zoet water en daarom met grote verschillen in elektrische geleidbaarheid (van 2 tot 60 dS m^{-1}). Hoge grondwaterstanden hadden geen significante effecten op de rijstopbrengst, behalve als het water een hoog zoutgehalte had. Daarom is beheersing van grondwater alleen nodig als dit erg zout is. Verscheidene statistische en wiskundige procedures werden toegepast om rijstopbrengsten van percelen te vergelijken. De gewone correlatiecoëfficiënt werd gebruikt om een puntsgewijze vergelijking tussen opbrengst en bodemvariabelen te maken. Door stapgewijze regressie was een voorspelling mogelijk van opbrengst uit bodemvariabelen. De wet van het minimum van de limiterende factoren, voor het eerst voorgesteld door Von Liebig, identificeerde dat deel van het opbrengstgat (ongeveer 3000 kg ha^{-1}) dat aan bodemfactoren toegeschreven kan worden. Een ongeïdentificeerd opbrengstgat van 1000 kg ha^{-1} bleef over. Verscheidene andere factoren zouden echter ook effect gehad kunnen hebben, zelfs als ze hier niet naar voren zijn gekomen. Deze statistische procedures geven echter geen mechanistische verklaring voor de plant-bodem processen. Dankzij de geïrrigeerde omstandigheden kunnen oogstgegevens voor een bepaald jaar worden geëxtrapoleerd naar andere jaren omdat de gebruikelijke effecten van waterbeperking bij ongeïrrigeerde mediterrane omstandigheden hier niet aanwezig zijn. Daarom kunnen de resultaten van 1995 gebruikt worden om bepaalde manieren van bedrijfsvoering in bepaalde gebieden te suggereren om tot een relatief hoge efficiëntie van gebruik van natuurlijke hulpbronnen te komen, ook voor jaren waarvoor geen statistische analyses bestaan.

Hoofdstuk 7 richt zich op de kwantificering van de groei van rijst op veldniveau in relatie tot gewastoestand en bodemeigenschappen. De rijstgroei werd gevolgd en bodemeigenschappen werden gemeten. De opbrengst werd gerelateerd aan de bodemeigenschappen door middel van een deductief proces om de opbrengstbepalende factoren vast te stellen. Eerst werden (i) oogstcomponenten, vervolgens (ii) variabelen met betrekking tot gewastoestand, en tenslotte (iii) bodemeigenschappen geïdentificeerd. Om de verschillende groepen variabelen te verbinden werden correlatieanalyse en een operationalisering van de wet van het minimum ("Min-Max" methode) toegepast. Voor kwantificering van opbrengst op veldniveau waren naast aantallen pluimen en bloempjes de fractie korrels met necrose (korrelkwaliteit), de intensiteit van onkruidgroei en de ruimtelijke heterogeniteit binnen velden benodigde faktoren. De nauwkeurigheid van opbrengstvoorspelling uit deze vijf variabelen was heel hoog (r^2_{adj} = 0,94). Vier hoofdgroepen van oorzaken beperkten de groei van rijst: (i) kaliumtekort en (ii) zinktekort, beide met een sterk antagonisme met natrium, (iii) slechte vestiging van de planten (een minimum plantdichtheid van 160 - 180 planten per m^2 was nodig voor maximale opbrengst) en (iv) de lengte van het groeiseizoen, vooral de lengte van de periode vóór het schieten waarin de potentiële grootte van de opbrengst wordt bepaald. De nauwkeurigheid van de opbrengstvoorspelling uit deze variabelen was redelijk hoog (r^2_{adj} = 0,76). Hoe groter de "causale afstand" tussen opbrengst en de bepalende faktoren, hoe lager de voorspellingsnauwkeurigheid. Kalium- en zinktekorten in de plant werden voornamelijk geïnduceerd door bodemsaliniteit. Zinktekort was niet ernstiger bij hoge bodem-pH. Bij zoute bodems leidde hoog K niet tot een hogere K opname. Het is niet duidelijk of in de zoute bodems van het studiegebied toevoeging van Zn leidt tot een toename van de Zn opname. De lengte van de groeiperiode hing voornamelijk af van de temperatuur, en ook van bodemeigenschappen. Een hoog kleigehalte in de toplaag was gunstig voor een lange groeiduur, betere homogeniteit van planten per eenheid bodemoppervlak, en voldoende gehaltes van kalium en zink in de plant.

Hoofdstuk 8 is een algemene discussie van het project, waarbij de blik ook wordt gericht op andere rijstverbouwende gebieden met een gematigd klimaat zoals de Camargue (Frankrijk), de Povlakte (Italië) en het rivierengebied van New South Wales (Australië). De effecten van de weersomstandigheden op de groei van rijst zijn gekwantificeerd met een verklarend model, maar de effekten van bodemeigenschappen werden statistisch behandeld. Verklarende modellen voor het effect van bodemeigenschappen moeten dus nog worden ontwikkeld. Dit onderzoek heeft aangetoond dat eenvoudig verkrijgbare bodemgegevens 75% van het opbrengstgat kunnen verklaren. Om deze verschillen ook procesmatig te begrijpen is verdere opname van bodemgegevens in gewasgroeimodellen voor de groei van geïrrigeerde natte rijst noodzakelijk.

Dit onderzoek heeft laten zien dat er een groot gat gaapt tussen wat potentieel kan en wat werkelijk wordt gehaald. Wij hebben het "beste boeren" scenario onderzocht. We hebben opbrengstverschillen tussen "goede/slechte boeren" en "goede/slechte bodems" vergeleken en geanalyseerd. Sommige boeren doen het heel goed, maar andere minder. Dit proefschrift opent de mogelijkheid om verder te gaan dan alleen maar ongericht experimenteel onderzoek. Toekomstig onderzoek zou gericht moeten zijn op ontwikkeling van beslissingsondersteuningssystemen voor landbouw op de belangrijkste bodemeenheden. *Wat wanneer* te doen is de kwestie. Op welke manier verschillen bodems functioneel van elkaar? Boeren en beleidsvoerders zouden dan zelf moeten kunnen beslissen wat te doen, gebaseerd op een grondige kennis van het gebied en zijn natuurlijke processen!

Resumen (summary in Spanish)

Esta tesis desarrolla un análisis cuantitativo del cultivo del arroz, en siembra directa y bajo pleno riego, en relación a las condiciones de clima y suelo en el Delta del Ebro, España. El objetivo general es entender las interrelaciones del sistema formado por "arroz-clima-suelo" en el área de estudio. ¿Por qué se cultiva arroz en la casi totalidad del Delta del Ebro? ¿Cómo crece y se desarrolla el arroz? ¿Cuál es la producción máxima en el Delta del Ebro? ¿Qué propiedades del suelo están limitando, y cómo afectan en el crecimiento del cultivo (p.e., estas propiedades del suelo provocan déficit de nitrógeno, de zinc o de ..., lo que se traduce en una reducción del número de granos, del peso de los granos o de ...)?
El objetivo general se divide en los siguientes objetivos específicos:
(1) Determinar las principales propiedades de los suelos y su distribución, comprender su funcionamiento y crear una base de datos geográfica.
(2) Determinar la curva de crecimiento óptima para el cultivo del arroz basada en el clima (temperatura y radiación), sin limitaciones edáficas. Es decir, definir la producción potencial.
(3) Determinar la interrelación entre las propiedades del suelo y el crecimiento del arroz. El objetivo es comprender *qué* propiedades del suelo influyen en el cultivo del arroz y *cómo* afectan. Básicamente, identificar qué propiedades del suelo contribuyen en mayor grado a la diferencia entre la producción potencial y la producción real; y comprender cómo estas propiedades del suelo modifican el estado del cultivo repercutiendo, en definitiva, en la producción.

El relieve del Delta del Ebro es llano y su paisaje se caracteriza por el monocultivo de arroz en casi toda la superficie cultivable. Dados los factores de mercado y políticas ambientales actuales, la principal razón por la que se cultiva arroz es la existencia de un nivel freático salino cercano a la superficie en gran parte del área. La salinidad también perjudica el cultivo del arroz, como muestra este estudio. Sin embargo, el flujo continuo de agua de riego en el cultivo del arroz previene el ascenso capilar del agua freática salina, evitando así un incremento de la salinidad del suelo. Para suministrar y drenar esta gran cantidad de agua (en promedio se usan 4000 litros de agua por kilogramo de arroz producido), se requiere una densa red de canales de riego y de drenaje.
En el capítulo 2 se presenta una descripción detallada de las condiciones ambientales (clima, recursos de agua, geomorfología), la base socio-económica y el sistema de producción de arroz en el Delta del Ebro.

El capítulo 3 responde al primer objetivo específico, estudiando los suelos, su distribución en el espacio y sus características en la zona norte del Delta del Ebro (el margen izquierdo). Los suelos se han clasificado en base a (i) su desarrollo, (ii) su textura, (iii) su grado de drenaje y (iv) su salinidad. En las áreas sin desarrollo del suelo, las características edáficas reflejan la variabilidad de los sedimentos originales. Las texturas de los sedimentos se relacionan con los ambientes sedimentarios: en el ambiente fluvial, por ejemplo, el diámetro del sedimento es mayor cuánto más cerca está de la zona de descarga, con un rango de texturas que va desde arena fina a arcilla. Las tormentas del mar y las olas han actuado dispersando los sedimentos y allanando los rasgos topográficos. El grado de drenaje se ha cuantificado y la salinidad del suelo se ha medido, estudiándose sus causas y distribución.

Los tipos de suelo (detallados en la Fig. 3.3 y Tabla 3.4) se pueden agrupar en:

- Suelos no-desarrollados con texturas medias y finas, los cuales pueden ser bien drenados y no-salinos (NM1,2) o imperfectamente drenados y moderadamente salinos (NM3,4,5). Se encuentran en los bancos del río actual o de antiguos ríos. Especialmente los suelos NM1,2 permiten rotaciones de cultivos y son muy valorados por esta "flexibilidad" de manejo. Para el cultivo del arroz, sin embargo, todos ellos carecen de un cierto porcentaje de arcilla en el horizonte superficial.
- Suelos no-desarrollados con texturas medias y finas, los cuales están escasamente y muy escasamente drenados. Se encuentran en la llanura de inundación que está cerca de la plataforma continental (NM9), en los antiguos cauces de río y fondos de laguna (NM8), y en zonas de transición (NM6,7). Los suelos NM9 no son salinos porque el agua freática en esa zona no es salina. Esto es debido a que esa zona está relativamente elevada con respecto al resto del Delta. Los suelos NM6,7,8 son muy salinos alcanzando valores máximos de la conductividad eléctrica en la pasta saturada (CE_e) de 30 dS m^{-1}. Teniendo en cuenta que un suelo con más de 4 dS m^{-1} de CE_e se considera salino, ¡un 30% de la superficie cultivable del margen izquierdo del Delta del Ebro, al traspasar este límite, es salina!. La elevada salinidad de estos suelos impide el crecimiento de otro cultivo distinto al arroz. Además, también reduce el crecimiento del arroz como se muestra en los capítulos 6 y 7 de esta tesis.
- Suelos no-desarrollados con texturas gruesas. Se encuentran cerca del mar (NC5,7,9) y en los extremos de los cursos de río abandonados (NC3). Esto suelos son arenas con o sin una capa fina de sedimentos fluviales en la superficie. Su grado de drenaje depende de la proximidad al mar. Los suelos NC5,7,9 son moderadamente salinos debido a los efectos contrapuestos de proximidad al mar y elevada percolación, mientras que los NC3 no son salinos. Su fertilidad es baja para el cultivo del arroz debido principalmente al bajo contenido en arcilla y limo. Actualmente, sin embargo, se consiguen producciones de arroz moderadas con

tecnología apropiada, incluyendo de dos a cuatro fertilizaciones de cobertera y un buen control de las enfermedades fúngicas.

- Suelos desarrollados con acumulación de carbonato cálcico (DM3,4,5,7) o con presencia de un horizonte hístico (DP9), entre 0 y 100 cm de profundidad. Se encuentran cerca de la plataforma continental pero su extensión es muy limitada. Son los mejores suelos para el cultivo del arroz, ya que tienen un alto contenido en arcilla y limo, y baja salinidad.

La metodología de la prospección de suelos fue innovadora al combinar conocimientos de la zona, con el muestreo por cuadrícula y medidas a corta distancia. Se creó una base de datos geográfica (SGD) o un sistema de información geográfico para almacenar, analizar y presentar los datos de los suelos. La SGD tiene muchas ventajas respecto a un mapa tradicional, destacando su flexibilidad en la gestión de los datos. Se usaron dos métodos para definir las características del territorio:

- El "modo objeto" asume que las características del territorio se definen por una posición geométrica y una forma. Con esta metodología se crearon mapas de unidades discretas de territorio que contenían el tipo de suelo, la clase textural desde la base del horizonte de baja permeabilidad (≈ 30 cm) hasta 100 cm y la textura del horizonte superficial. Los límites se dibujaron en base al modelo conceptual del prospector, combinando los datos de suelo con ortofotomapas de la zona.
- El "modo terreno" asume que las características del territorio son continuas en el espacio. Se crearon mapas continuos de elevación y de varias propiedades del suelo, relevantes en la zona de estudio. Los mapas se elaboraron por interpolación de los datos de los suelos.

Las diferencias entre unidades geomorfológicas, y sus efectos específicos en los suelos, se expresaron mejor en el modo objeto. Las diferencias en una unidad, de elevación y propiedades del suelo sencillas (como salinidad y grado de drenaje) que cambian gradualmente, se expresaron mejor con el segundo método. Para el estudio de uso de tierras en sistemas agrícolas, es de gran valor el diseño de esquemas que a priori combinen ambos métodos desde la etapa de obtención de datos.

El capítulo 4 proporciona la respuesta al segundo objetivo específico y a otras preguntas relevantes como; ¿cuáles son los requerimientos del cultivo del arroz? ¿Cuáles son las diferencias de cultivo entre una variedad de grano corto y otra de grano largo (sin considerar los efectos del suelo)? ¿Cuáles son los niveles óptimos de nitrógeno? Se monitorizó bajo buenas condiciones de suelo y manejo una variedad de grano corto (Tebre) y otra de grano largo (L-202) representativas del Delta del Ebro. La producción potencial de arroz se estableció como función de condiciones ambientales sobre las que el agricultor no ejerce influencia: temperatura y radiación. El modelo descriptivo ORYZA1 (Kropff et al., 1994) se usó para simular el crecimiento y desarrollo del arroz así como el índice de área foliar, bajo condiciones de producción potencial. La finalidad de este estudio era evaluar la validez y adecuación de ORYZA1 en condiciones Mediterráneas. ORYZA1 se calibró y validó principalmente con datos de campo de 1994 a 1996. En concreto se calibró el desarrollo fenológico, la producción diaria de materia seca, y el desarrollo del área foliar. Tebre y L-202 no presentaron diferencias significativas en la tasa de desarrollo general. Sin embargo, el periodo de pre-floración fue más largo y el de post-floración más corto en L-202 que en Tebre. Esto produjo diferencias en la translocación, la capacidad de ahijamiento, el peso de los granos y el índice de cosecha. Las siguientes características del cultivo fueron similares entre ambas variedades: el coeficiente de extinción de luz (que se incrementó de 0.35 a 0.61 al avanzar el estado de desarrollo), la distribución dinámica de nitrógeno (con valores óptimos de nitrógeno en las hojas del 3.5% en la iniciación de panícula y 2.5% en la floración), la partición de los asimilados, la tasa relativa de secado de hojas, la tasa relativa de incremento del área foliar durante la primera etapa de crecimiento exponencial (0.009 $(^{\circ}Cd)^{-1}$ con una temperatura base de 10°C), el área foliar específica (entre 15 y 25 m^2 kg^{-1} materia seca de hoja), y el área del tallo específica que disminuyó enormemente al avanzar el ciclo (entre 2 y 20 m^2 kg^{-1} materia seca de tallo). Bajo condiciones de crecimiento óptimas, se observaron valores de 450 para Tebre y 600 para L-202 de panículas por metro cuadrado. Los mejores resultados en la simulación se obtuvieron al considerar que el índice del área foliar representa sólo el área del limbo, sin contribución ni del área de la vaina ni de la caña al aparato fotosintético de la planta de arroz. El modelo se ajustó correctamente hasta el momento de la floración. A partir de la floración aparecieron divergencias que se incrementaron especialmente durante la maduración. En este último periodo el cultivo no creció más, mientras que en la simulación siguió creciendo. Esta reducción de la tasa de crecimiento fue acompañada de un aumento de la tasa relativa de hojas secas y del secado de los granos. Las principales causas de error pueden ser un conocimiento insuficiente de los procesos de maduración y de la limitación del sumidero (número de granos). Entre la producción potencial y la máxima actual permaneció una diferencia considerable de 2000 kg ha^{-1}. Un estudio de la variabilidad climática en los últimos 10 años mostró una variación pequeña, pero similar (coeficiente de correlación de 0.7) entre producciones de arroz simuladas y medidas.

Para actuar de forma agronómicamente correcta, al agricultor le interesa conocer el estado del cultivo del arroz. En agricultura, el seguimiento del crecimiento y desarrollo del cultivo, así como la pronta estimación de la producción final presentan un gran interés. En el capítulo 5 se estima la biomasa y el índice de área foliar (LAI) del arroz mediante la reflectancia a nivel de campo con un radiómetro portátil. Primero se calcularon los índices de vegetación (RVI, NDVI, WDVI, PVI) a partir de la reflectancia del cultivo. Luego se calculó la fracción interceptada de radiación fotosintéticamente activa (PAR), f_{PAR}, a partir de los índices de vegetación, en base a un modelo de reflectancia física. WDVI y PVI, índices que corrigen la reflectancia del suelo, mostraron una relación más lineal y con menos dispersión que NDVI y RVI. La relación de NDVI con f_{PAR} dio una buena predicción durante el periodo vegetativo, pero se saturó con $f_{PAR} \geq 0.4$. La reflectancia del suelo necesaria para PVI y WDVI fue fácilmente estandarizada en campos permanentemente inundados (10.2% = reflectancia en el rojo; 7.0% = reflectancia en el infrarrojo cercano). Se discuten dos procedimientos: (a) la estimación de LAI y (b) la estimación de biomasa. El primer procedimiento relaciona la f_{PAR} con el LAI por medio del coeficiente de extinción (K), el cual varía a lo largo del ciclo del arroz. El comportamiento dinámico de K se analizó y calibró para los distintos estados de desarrollo. Una vez que K fue establecido, el LAI se estimó directamente a partir de la f_{PAR}. Este procedimiento explicó sólo el 67% de la variación del LAI. El segundo procedimiento utiliza el modelo de Monteith que requiere un parámetro específico del cultivo, el factor de conversión (α) de PAR interceptada a materia seca. Para el arroz en siembra directa, los valores de α fueron de 2.25 g MJ^{-1} para la biomasa aérea (incluyendo las hojas secas) a lo largo del ciclo del arroz, disminuyendo hacia el final del ciclo. La estimación de la biomasa a partir de datos de teledetección, resultó más fiable que la estimación del LAI.

La respuesta al tercer y último objetivo específico, o la integración final entre las condiciones de crecimiento del arroz y las propiedades del suelo se expone en los capítulos 6 y 7. En el capítulo 6 se identificó y cuantificó qué propiedades del suelo limitan el crecimiento del arroz y en el capítulo 7 qué efectos causan estas propiedades del suelo, junto con la gestión del agricultor, en el estado del cultivo y en consecuencia en la producción. Se seleccionaron un total de 50 campos distribuidos por todo el Delta, donde todas las variables ambientales y sus interrelaciones se evaluaron a nivel de campo. Por una parte, se describieron las unidades de suelo y se midieron las principales características del horizonte superficial. Por otra, se midieron las características del arroz durante el ciclo de crecimiento: número de plantas por unidad de superficie, características nutritivas de las plantas, duración de los distintos periodos de desarrollo, área foliar en el momento de la iniciación de panícula y en la floración, presencia de malas hierbas, presencia de enfermedades y, finalmente, los componentes del rendimiento: se observó una gran variabilidad en el crecimiento del arroz y en la cosecha final.
El capítulo 6 muestra las propiedades del suelo que influyeron en mayor medida en la cosecha de arroz: (i) la CIC del horizonte superficial, y su contenido en arcilla y limo; (ii) el pH del horizonte superficial en el rango de 6.7 a 7.9; (iii) la salinidad del suelo, que se halló relacionada negativamente con la cosecha. La salinidad del suelo se halló altamente relacionada con la conductividad eléctrica del agua freática. El origen del agua freática es marino y existen grandes diferencias en su conductividad

eléctrica (de 2 a 60 dS m^{-1}). El agua freática cercana a la superficie no tuvo efectos significativos sobre la cosecha del arroz, excepto cuando dicha agua tenía un alto contenido en sales. Por consiguiente, el agua freática debe ser controlada sólo si es altamente salina. Para comparar las diferencias entre las cosechas de arroz de los diferentes campos, se utilizaron varios métodos matemáticos y estadísticos. El coeficiente de correlación simple fue útil para determinar una comparación entre la cosecha y las variables del suelo. La regresión permitió la predicción de la cosecha a partir de las variables del suelo. La Ley del Mínimo de los factores limitantes, propuesta por primera vez por Von Liebig, explicó la diferencia de producción causada por las propiedades del suelo (aproximadamente 3000 kg ha^{-1}). Permaneció sin explicar una diferencia de producción de 1000 kg ha^{-1}. Otros varios factores podrían tener efectos en la predicción, a pesar de no haberse manifestado. Estos procedimientos estadísticos, sin embargo, no proporcionan explicaciones mecanísticas de los procesos entre la planta y el suelo. Al no estar presentes los efectos de limitación de agua de la agricultura de secano Mediterránea, los datos de cosecha de un año concreto pueden ser representativos para otros años en condiciones de campo inundado. Por tanto, los resultados obtenidos en el 1995 pueden ser usados para sugerir ciertos tipos de gestión, que permitan una gran eficiencia del uso de los recursos naturales en años en los que no existan estudios.

En el capítulo 7 se cuantifica el crecimiento del arroz a nivel de parcela en relación con el estado del cultivo y las propiedades del suelo. Se obtuvieron datos del crecimiento del arroz y se midieron las propiedades del suelo. La cosecha se relacionó con las propiedades del suelo mediante un proceso deductivo que identificaba los factores determinantes de la cosecha. Se identificaron (i) los componentes de cosecha, (ii) las variables relacionadas con el estado del cultivo, y (iii) las propiedades del suelo. Para interrelacionar los distintos tipos de variables, se utilizó un análisis de correlación y un método operacional de la Ley del Mínimo (método "Min-Max"). Para cuantificar la cosecha a nivel de parcela, además del número de panículas y espiguillas por unidad de área, fue necesario tener en cuenta la fracción de granos con necrosis (calidad de granos), la infestación de malas hierbas, y la heterogeneidad espacial dentro de cada campo. El ajuste en la predicción de la cosecha con estas cinco variables fue muy bueno (r^2_{adj} = 0.94). Cuatro grupos principales de causas limitaban el crecimiento del arroz: (i) déficit de potasio, (ii) déficit de zinc, donde se observó un fuerte antagonismo de ambos factores con el sodio, (iii) baja densidad de plantas (donde era necesario un mínimo de 160-180 plantas m^{-2} para maximizar la cosecha), y (iv) la duración del periodo de crecimiento, especialmente la duración del periodo pre-floración, en el cual se determina el tamaño potencial de la cosecha. El ajuste en la predicción de la cosecha a partir de estas variables fue moderadamente bueno (r^2_{adj} = 0.76). Cuanto más larga es la "distancia causal" entre la cosecha y sus factores determinantes, menor es la precisión en la predicción. Los déficits de potasio y zinc en la planta fueron causados principalmente por la salinidad del suelo. El déficit de zinc no estaba relacionado con el pH alto del suelo. Valores elevados de potasio en suelos salinos, no incrementaron la absorción de potasio por la planta. Queda por determinar si la adición de zinc en suelos salinos del área de estudio, incrementa la absorción de zinc. La duración del periodo de crecimiento fue determinada principalmente por la temperatura, pero también por las propiedades del suelo. Un alto contenido en arcilla del horizonte superficial favoreció el ciclo largo, la homogeneidad de las plantas por unidad de superficie, y adecuados niveles de potasio y zinc en la planta.

El capítulo 8 presenta una discusión general sobre el proyecto, que trata de incorporar una visión amplia del cultivo del arroz en clima templado en otras áreas como la Camarga (Francia), el valle del Po (Italia) y el distrito de New South Wales (Australia). Se discuten las principales características en relación al cultivo de arroz puramente agronómicas, -como los suelos, el clima, el agua, la gestión agrícola-, y también factores socio-económicos como los elevados costes de producción, la presión ambiental y los acuerdos del GATT. Los efectos de las condiciones del clima sobre el cultivo del arroz se han cuantificado con un modelo descriptivo. Los efectos de las propiedades del suelo sobre el arroz se han tratado estadísticamente. Por tanto, falta desarrollar modelos descriptivos que incorporen los efectos de las propiedades del suelo. Este estudio ha mostrado que datos de suelo fácilmente disponibles pueden explicar el 75% de la diferencia entre la producción potencial y la obtenida. Para comprender realmente estas diferencias a nivel de procesos entre la planta y el suelo, es necesaria la futura incorporación de datos de suelos en modelos de crecimiento del cultivo del arroz-inundado.

La investigación muestra que existe una gran diferencia entre la producción potencial y la real. Hemos explorado el escenario de "los mejores agricultores". Hemos comparado y analizado diferencias entre "agricultores buenos/malos" y "suelos buenos/malos". Algunos agricultores aplican los principios agronómicos correctamente, y otros no tanto. Esta tesis ofrece la posibilidad de ir más allá del trabajo experimental puramente al azar. Las investigaciones futuras deberían orientarse hacia el desarrollo de sistemas de apoyo a la toma de decisiones para la gestión agrícola y ambiental en las distintas unidades de territorio. *Qué* hacer y *cuándo* es la cuestión principal. ¿De qué forma son los suelos funcionalmente distintos? Los agricultores y gestores del futuro deberían poseer las herramientas necesarias para decidir ellos mismos qué hacer, en base a un conocimiento exhaustivo de la zona y a sus procesos naturales.

Resum (summary in Catalan)

Aquesta tesi desenvolupa una anàlisi quantitativa del conreu de l'arròs, en sembra directa i en reg a tesa, en relació a les condicions del clima i del sòl al Delta de l'Ebre, Espanya. L'objectiu general és entendre les interrelacions del sistema format per "l'arròs-el clima-el sòl" a l'àrea d'estudi. Per què es cultiva arròs gairebé a tot el Delta de l'Ebre? Com creix i es desenvolupa l'arròs? Quina és la producció màxima al Delta de l'Ebre? Quines propietats del sòl són limitants, i com afecten al creixement del cultiu? (p.e. aquestes propietats del sòl provoquen un dèficit de nitrogen, de zinc o de ..., i aquests dèficits es tradueixen a una reducció del número de grans, del pes dels grans, o de ...)?

L'objectiu general es divideix en els següents objectius específics:

(1) Determinar les principals propietats dels sòls i la seva distribució, comprendre els seus factors de funcionament i crear una base de dades geogràfica.

(2) Determinar la corba de creixement òptima pel conreu de l'arròs basada en el clima (temperatura i radiació), sense limitacions edàfiques. És a dir, definir la producció potencial.

(3) Determinar la interrelació entre les propietats del sòl i el creixement de l'arròs. L'objectiu és comprendre quines propietats del sòl influeixen al conreu de l'arròs i com l´afecten. Bàsicament, identificar quines propietats del sòl contribueixen en major mesura a la diferència entre la producció potencial i la producció real; i comprendre com aquestes propietats del sòl modifiquen l'estat del conreu i repercuteixen, en definitiva, en la producció.

El relleu del Delta de l'Ebre és pla i el seu paisatge es caracteritza pel monocultiu de l'arròs a quasi tota la superfície conreada. Tenint en compte els factors presents de mercat i la política medi ambiental, la principal raó per la qual es cultiva arròs és l'existència a gran part de l'àrea d'un nivell freàtic salí proper a la superfície. La salinitat també perjudica el conreu de l'arròs, com mostra aquest estudi. Tanmateix, el flux continu d'aigua de reg al cultiu de l'arròs evita l'ascens capil·lar de l'aigua freàtica salina, impedint així un increment de la salinitat del sòl. Per a subministrar i drenar aquesta gran quantitat d'aigua (com a terme mig s'utilitzen 4000 litres d'aigua per quilògram d'arròs produït), es requereix un densa xarxa de canals de reg i drenatge.

Dins del capítol 2 es presenta una descripció detallada de les condicions ambientals (clima, recursos d'aigua, geomorfología), la base socio-econòmica i el sistema de producció d'arròs al Delta de l'Ebre.

El capítol 3 respon al primer objectiu específic, estudiant els sòls, la seva distribució a l'espai i les seves característiques a la zona nord del Delta de l'Ebre (el marge esquerre). Els sòls s'han classificat en base a (i) el seu desenvolupament, (ii) les seves textures, (iii) el seu grau de drenatge i (iv) la seva salinitat. A les àrees on no existeix un desenvolupament del sòl, les característiques edàfiques reflecteixen la variabilitat dels sediments originals. Les textures dels sediments es relacionen amb els ambients sedimentaris: a l'ambient fluvial, per exemple, el diàmetre del sediment és major quant més a prop es troba de la zona de descàrrega, amb un rang de textures que va des de l'arena fina fins a l'argila. Les tempestes del mar i les onades han actuat dispersant els sediments i aplanant els trets topogràfics. El grau de drenatge s'ha quantificat i la salinitat del sòl s'ha mesurat, estudiant-hi les seves causes i la seva distribució.

Els tipus de sòl (detallats a la Taula 3.4 i Fig. 3.3) es poden agrupar en:

- Sòls no-desenvolupats de textures mitges i fines, els quals poden ser ben drenats i no-salins (NM1,2) o imperfectament drenats i moderadament salins (NM3,4,5). Es troben als bancs del riu actual o d'antics rius. Especialment els sòls NM1,2 permeten rotacions de conreu i són molt valorats per aquesta "flexibilitat" de maneig. Per altra banda, per al conreu de l'arròs a tots ells els manca un cert percentatge d'argila a l'horitzó superficial.
- Sòls no-desenvolupats de textures mitges i fines, els quals estan escassament i molt escassament drenats. Es troben a la plana d'inundació que es sitúa vora la plataforma continental (NM9), a les antigues lleres de riu i llacunes (NM8) i a les zones de transició (NM6,7). Els sòls NM9 no són salins perquè l'aigua freàtica d'aquesta zona no és salina. Això es degut a que aquesta zona es troba relativament elevada respecte a la resta del Delta. Els sòls NM6,7,8 són molt salins assolint valors màxims de la conductivitat elèctrica a la pasta saturada (CE_e) de 30 dS m^{-1}. Tenint en compte que un sòl amb més de 4 dS m^{-1} de CE_e es considera salí, un 30% de la superfície conreada al marge esquerre del Delta de l'Ebre, quan traspassa aquest límit, és salina! L'elevada salinitat d'aquests sòls impedeix el creixement d'un altre cultiu que no sigui arròs. A més a més, també redueix el creixement de l'arròs com es mostra al capítols 6 i 7 d'aquesta tesi.
- Sòls no-desenvolupats de textures grosses. Es troben prop del mar (NC5,7,9) i als extrems de les lleres de riu abandonades (NC3). Aquests sòls són arenes amb o sense una capa fina de sediments fluvials a la superfície. El seu grau de drenatge depèn de la proximitat al mar. Els sòls NC5,7,9 són moderadament salins degut als efectes contraposats de proximitat al mar i elevada percolació, mentre que els NC3 no són salins. La seva fertilitat és baixa degut principalment al baix contingut d'argila i llim. Actualment s'aconsegueixen produccions moderades amb tecnologia apropiada, incloent de dos a quatre fertilitzacions de cobertera i un bon control de les malalties fúngiques.

- Sòls desenvolupats per acumulació de carbonat càlcic (DM3,4,5,7) o per la presència d'un horitzó hístic (DP9), entre 0 i 100 cm de fondària. Es troben prop de la plataforma continental però la seva existència és molt limitada. Són els millors sòls per al conreu de l'arròs, ja que tenen un alt contingut en argila i llim, i baixa salinitat.

La metodologia de la prospecció va ser innovadora ja que va combinar coneixements de la zona, amb el mostreig per quadrícula i mesures a curta distància. Es va crear una base de dades geogràfica (SGD) o un sistema d'informació geogràfica per tal d'emmagatzemar, analitzar i presentar les dades dels sòls. La SGD té moltes avantatges respecte a un mapa tradicional, destacant la seva flexibilitat en la gestió de dades. Es van utilitzar dos mètodes per definir les característiques de territori:

- El "mode objecte", que assumeix que les característiques del territori es defineixen per una posició geomètrica i una forma. Amb aquesta metodologia es van crear mapes d'unitats discretes de territori que contenien el tipus de sòl, la classe textural des de la base de l'horitzó de baixa permeabilitat fins a 100 cm i la textura de l'horitzó superficial. Els límits es van dibuixar en base al model del prospector, combinant les dades de sòls amb ortofotomapes de la zona.
- El "mode terreny", que assumeix que les característiques del territori són continues a l'espai. Es van crear mapes continus d'elevació i de vàries propietats del sòl, rellevants a la zona d'estudi. Els mapes es van elaborar per interpolació de les dades dels sòls.

La diferència entre unitats geomorfològiques, i els seus efectes específics als sòls, es van expressar millor en el mode objecte. Les diferències dins d'una unitat, d'elevació i de propietats del sòl senzilles (com salinitat i grau de drenatge) que canvien gradualment, es van expressar millor en el segon mètode. Per a l'estudi d'ús de terres en els sistemes agrícoles, és de gran valor el disseny d'esquemes que a priori combini ambdós mètodes des del moment de recol·lecció de dades.

El capítol 4 proporciona la resposta al segon objectiu específic i a d'altres preguntes rellevants com ara; quins són els requeriments del conreu de l'arròs?; quines són les diferències de conreu entre una varietat de gra curt i una de gra llarg (sense considerar els efectes del sòl)?, quins són els nivells òptims de nitrogen? Es va fer un seguiment del conreu, sota bones condicions de sòl i maneig, d'una varietat de gra curt (Tebre) i una de gra llarg (L-202) representatives del Delta de l'Ebre. La producció potencial d'arròs es va establir com a funció de condicions ambientals sota les que l'agricultor no exerceix influència: temperatura i radiació. El model descriptiu ORYZA1 (Kropff et al., 1994) es va utilitzar per simular el creixement i desenvolupament de l'arròs així com l'índex d'àrea foliar, sota condicions de producció potencial. La finalitat d'aquest estudi era avaluar la validesa i adequació de ORYZA1 sota condicions Mediterrànies. ORYZA1 es va calibrar i validar principalment amb dades de camp de 1994 a 1996. Concretament es va calibrar el desenvolupament fenològic, la producció diària de matèria seca, i el desenvolupament de l'àrea foliar. Tebre i L-202 no van presentar diferències significatives a la taxa de desenvolupament general. Malgrat això, el període de pre-floració va ser més llarg i el de post-floració més curt a L-202 que al Tebre. Això va produir diferències a la translocació, la capacitat d'afillament, el pes dels grans i l'índex de collita. Les següents característiques del cultiu foren similars entre ambdues varietats: el coeficient d'extinció de llum (que es va incrementar de 0.35 a 0.61 a mesura que avançava l'estat de desenvolupament), la distribució dinàmica de nitrogen, (amb valors òptims de nitrogen a les fulles de 3.5% a la iniciació de panícula i de 2.5% a la floració), la partició dels assimilats, la taxa relativa d'assecament de fulles, la taxa relativa d'increment d'àrea foliar durant la primera etapa de creixement exponencial (0.009 $(^{\circ}Cd)^{-1}$ amb una temperatura base de 10°C), l'àrea foliar específica (entre 15 i 25 m^2 kg^{-1} matèria seca de fulla), i l'àrea de la tija específica (entre 2 i 20 m^2 kg^{-1} matèria seca de tija). Sota condicions de creixement òptim, es van observar 450 i 600 panícules m^{-2} per a Tebre i L-202, respectivament. Els millors resultats a la simulació es van obtenir quan es va considerar que l'índex d'àrea foliar representa només l'àrea del limbe, sense contribució ni de l'àrea de la beina ni de la canya a l'aparell fotosintètic de la planta d'arròs. El model es va ajustar correctament fins al moment de la floració. A partir de la floració van aparèixer divergències que es van incrementar especialment durant la maduració. Durant aquest últim període el conreu no va créixer més, mentre que a la simulació continuà creixent. Aquesta reducció de la taxa de creixement va anar acompanyada d'un augment de la taxa relativa de fulles seques i de l'assecat dels grans. Les principals causes d'error poden ser uns coneixements insuficients dels processos de maduració i de la limitació de creixement per saturació de la capacitat d'acumulació de fotosintetitzats al gra. Entre la producció potencial i la màxima actual va romandre una diferència considerable de 2000 kg ha^{-1}. Un estudi de la variabilitat climàtica dels darrers 10 anys va mostrar una variació petita, però similar (coeficient de correlació de 0.7) entre produccions d'arròs simulades i mesurades.

Per tal d'actuar de forma agronòmicament correcta, al pagès li interessa saber l'estat del conreu de l'arròs. En el món agrari el seguiment del creixement i del desenvolupament del conreu, així com la prompta estimació de la producció final, presenten un gran interès. Al capítol 5 s'estimen la biomassa i l'índex d'àrea foliar (LAI) de l'arròs mitjançant la reflectància a nivell de camp amb un radiòmetre portàtil. Primer es van calcular els índexs de vegetació (RVI, NDVI, WDVI, PVI) a partir de la reflectància del conreu. Després es va calcular la fracció interceptada de radiació fotosintèticament activa (PAR), f_{PAR}, a partir dels índexs de vegetació , en base a un model de reflectància física. Els índexs que corregeixen la reflectància del sòl, WDVI i PVI, van mostrar una relació més lineal i amb menys dispersió que

NDVI i RVI. La relació de NDVI amb f_{PAR} va donar una bona predicció durant el període vegetatiu, però es va saturar amb $f_{PAR} \geq 0.4$. La reflectància del sòl necessària per a PVI i WDVI va ser fàcilment estandarditzada a camps permanentment inundats (10.2% = reflectància al roig; 7.0% = reflectància al infraroig proper). Es discuteixen dos procediments: (a) l'estimació del LAI i (b) l'estimació de la biomassa. El primer procediment relaciona la f_{PAR} amb el LAI mitjançant el coeficient d'extinció (K), el qual varia durant el cicle de l'arròs. El comportament dinàmic de K es va analitzar i calibrar per als diferents estats de desenvolupament. Un cop que K fou establert, el LAI es va estimar directament a partir de la f_{PAR}. Aquest procediment va explicar només el 67% de la variació del LAI. El segon procediment utilitza el model de Monteith que requereix un paràmetre específic del conreu; el factor de conversió (α) de PAR interceptada a matèria seca. Per a l'arròs en sembra directa, el valors de α foren de 2.25 g MJ^{-1} per la biomassa aèria (incloent les fulles seques) durant el cicle de l'arròs, disminuint cap al final del cicle. L'estimació de la biomassa mitjançant dades de teledetecció va resultar més fiable que la estimació del LAI.

La resposta al tercer i últim objectiu específic, o la integració final entre les condicions del creixement de l'arròs i les propietats del sòl s'exposa als capítols 6 i 7. Al capítol 6 es va identificar i quantificar quines propietats del sòl limiten el creixement de l'arròs i al capítol 7 quins efectes causen aquestes propietats, juntament amb la gestió del pagès, a l'estat del conreu i en conseqüència a la producció. Es van seleccionar un total de 50 camps distribuits per tot el Delta, on totes les variables ambientals i les seves interrelacions es van avaluar a nivell de camp. Per una banda, es van descriure les unitats del sòl i es van mesurar les principals característiques de l'horitzó superficial. Per l'altra banda, es van mesurar les característiques de l'arròs durant el cicle de creixement: número de plantes per unitat de superfície, deficiències nutritives a les plantes, duració dels diferents períodes de desenvolupament, àrea foliar al moment de l'iniciació de panícula i a la floració, presència de males herbes, presència de malalties i, finalment, els components del rendiment. Es va observar una gran variabilitat en el creixement de l'arròs i en la collita final!

El capítol 6 mostra com les propietats del sòl que van influir en major mesura a la collita d'arròs van ésser: (i) la CIC de l'horitzó superficial, i el seu contingut en argila i llim; (ii) el pH de l'horitzó superficial al rang de 6.7 a 7.9; (iii) la salinitat del sòl, la qual estava relacionada negativament amb la collita. La salinitat del sòl fou altament relacionada amb la conductivitat elèctrica de l'aigua freàtica. L'origen de l'aigua freàtica és marí, que barrejada amb l'aigua fresca dóna lloc a grans diferències en la seva conductivitat elèctrica (de 2 fins a 60 dS m^{-1}). L'aigua freàtica propera a la superfície no va tenir efectes significatius sobre la collita de l'arròs, excepte quan aquesta aigua tenia un alt contingut en sals. Per tant, l'aigua freàtica ha de ser controlada només si és altament salina. Per a comparar les diferències entre les collites d'arròs als diferents camps, es van utilitzar diferents mètodes matemàtics i estadístics. El coeficient de correlació simple fou útil per a determinar una comparació entre la collita i les variables del sòl. La regressió va permetre la predicció de la collita mitjançant les variables del sòl. La Llei del Mínim dels factors limitants, proposta per primer cop per Von Liebig, va explicar la diferència de producció causada per les propietats del sòl (aproximadament 3000 kg ha^{-1}). Altres diversos factors podrien tenir efectes en la predicció, encara que no es van manifestar. Aquests procediments estadístics, de totes maneres, no proporcionen explicacions mecanístiques dels processos entre la planta i el sòl. Al no ser-hi presents els efectes de limitació d'aigua de l'agricultura de secà Mediterrània, les dades de collita d'un any concret poden ser representatives per altres anys sota condicions de camp inundat. Per tant, els resultats obtinguts al 1995 poden ser utilitzats per a suggerir certs tipus de gestió, que permetin una gran eficiència de l'ús dels recursos naturals la resta dels anys.

Dins del capítol 7 es quantifica el creixement de l'arròs a nivell de parcel·la en relació amb l'estat del conreu i les propietats del sòl. Es van obtenir dades del creixement de l'arròs i es van mesurar les propietats del sòl. La collita es va relacionar amb les propietats del sòl mitjançant un procés deductiu que identificava els factors determinants de la collita. Es van identificar (i) els components de collita, (ii) les variables relacionades amb l'estat del conreu, i (iii) les propietats del sòl. Per a interrelacionar els diferents tipus de variables, es va utilitzar un anàlisi de correlació i un mètode operacional de la Llei del Mínim (mètode "Min-Max"). Per a quantificar la collita a nivell de parcel·la, a més a més del número de panícules i espiguetes per unitat d'àrea, fou necessari tenir en compte la fracció de grans amb necrosi (qualitat dels grans), la infestació de males herbes, i la heterogeneïtat espaial dins de cada camp. L'ajust en la predicció de collita amb aquestes cinc variables fou molt bo (r^2_{adj} = 0.94). Quatre grups principals de causes limitaven el creixement de l'arròs: (i) dèficit de potassi, (ii) dèficit de zinc, on es va observar un fort antagonisme d'ambdós factors amb el sodi, (iii) baixa densitat de plantes (on era necessari un mínim de 160-180 plantes m^{-2} per a maximitzar la collita, i (iv) la duració del període de creixement, especialment la duració del període pre-floració, on es determina la grandària potencial de la collita. L'ajust en la predicció de collita mitjançant aquestes variables fou moderadament bo (r^2_{adj} = 0.76). Quant més llarga és la "distancia causal" entre la collita i els seus factors determinants, menor és la precisió de la predicció. Els dèficits de potassi i zinc a la planta foren causats principalment per la salinitat del sòl. El dèficit del zinc no estava relacionat amb el pH alt del sòl. Valors elevats de potassi a sòls salins, no van incrementar l'absorció de potassi per la planta. Queda per determinar si l'adició de zinc a sòls salins de

l'àrea d'estudi, incrementa la seva absorció. La duració del període de creixement fou determinada principalment per la temperatura, però també per les propietats del sòl. Un alt contingut d'argila a l'horitzó superficial va afavorir el cicle llarg, l'homogeneïtat de plantes per unitat de superfície, i els adequats nivells de potassi i zinc a la planta.
El capítol 8 presenta una discussió general sobre el projecte, la qual tracta d'incorporar una visió amplia del conreu de l'arròs sota clima temperat a altres àrees com la Camarga (França), la vall del Po (Itàlia) i el districte de New South Wales (Australia). Es discuteixen les principals característiques agronòmiques respecte el conreu de l'arròs, -com els sòls, clima, aigua i gestió agrícola-, i també els factors socio-econòmics com els elevats costos de producció, la pressió ambiental i els acords del GATT. Els efectes de les condicions del clima sobre el conreu de l'arròs s'han quantificat amb un model descriptiu. Els efectes de les propietats del sòl sobre l'arròs s'han tractat estadísticament. Per tant, falta desenvolupar models descriptius que incorporin els efectes de les propietats del sòl. Aquest estudi ha mostrat que dades de sòl fàcilment disponibles poden explicar el 75% de la diferència entre la producció potencial i la obtinguda. Per tal de comprendre millor aquestes diferències a nivell de processos entre la planta i el sòl, és necessari la futura incorporació de dades de sòl a models de creixement del conreu de l'arròs-inundat.

La investigació mostra que existeix una gran diferència entre la producció potencial i la real. Hem explorat l'escenari "d'els millors agricultors". Hem comparat i analitzat diferencies entre "agricultors bons/dolents" i "sòls bons/dolents". Alguns agricultors apliquen els principis agronòmics correctament, i altres no tant! Aquesta tesi ofereix la possibilitat d'anar més enllà del treball experimental purament a l'atzar. Les investigacions futures haurien d'orientar-se cap el desenvolupament de sistemes d'ajut a la presa de decisions per la gestió agrícola i ambiental a les diferents unitats de terra. *Que* fer i *quan* fer-ho és la qüestió principal. De quina manera són els sòls funcionalment diferents? Els agricultors i gestors del futur haurien de posseir les eines necessàries per a decidir ells mateixos què fer, en base a un coneixement exhaustiu de la zona i els seus processos naturals.

References

Ahn, S.B., Ryu, I.S. and Yuk, C.S., 1991. Effects of percolation and soil amendments on the changes of physico-chemical properties and rice yield in paddy soil. Research reports of the rural development administration. Soil and Fertilizer, 33(2): 24-47.

Aliaga, J.R., 1984. Caracterización morfológica y bioquímica de variedades de arroz cultivadas en España. PhD thesis, University of Valencia, Valencia, 243 pp.

Angus, J.F., Bacon, P.E., Reinke, R.F. and Williams, R.L., 1993. Rice yield variability in Australia in relation to cool-temperature damage, N fertilizer and water depth. In: Proc. Third Symp. on the Impact of Climatic Change on Agricultural Production in the Pacific Rim. Central Weather Bureau, Taipei, Republic of China, pp. 11-28.

Asch, F., Dörffling, K. and Dingkuhn, M., 1995. Response of rice varieties to soil salinity and air humidity: a possible involvement of root-borne ABA. Plant and Soil, 177 (1): 11-19.

Baret, F., Olioso, A., Luciani, J.L. and Hanocq, J.F., 1989. Estimation à partir de mesures de rèflectance spectrale du rayonnement photosynthètiquement actif absorbè par une culture de blè. Agronomie, 9: 885-895.

Bayó, A., Loaso, C., Aragonés, J.M. and Custodio, E., 1992. Marine intrusion and brackish water in coastal aquifers of Southern Catalonia and Castelló (Spain): a brief survey of actual problems and circumstances. Study and modelling of saltwater intrusion into aquifers. Proceedings of the Saltwater Intrusion Meeting 1-6 November, 1992, CIMNE-UPC, Barcelona, pp. 741-766.

Bayó, A., Custodio, E. and Loaso, C., 1997. Las aguas subterráneas en el Delta del Ebro. Revista de Obras Públicas, number 3368, year 144, September 1997, Madrid. pp. 47-65. Special issue on "El Delta del Ebro/ The Ebro Delta".

Berge, H.F.M. Ten, Riethoven, J.J.M. and Wopereis, M.C.S., 1994. Numerical optimization of nitrogen fertilizer use in irrigated rice. DLO-Research Institute of Agrobiology and Soil Fertility, Wageningen, and International Rice Research Institute, Manila, 59 pp.

Beyrouty, C.A., Grigg, B.C., Norman, R.J. and Wells, B.R., 1994. Nutrient uptake by rice in response to water management. Journal of Plant Nutrition, 17(1): 39-55.

Birot, J.M., 1995. Du producteur au consommateur; Une forte notion de qualité. In: Riz; du débouché à la culture. Institut technique des céréales et des fourrages and Centre Français du Riz, Paris and Arles, pp. 12-13.

Bohra, J.S., Dörffling, H. and Dörffling, K., 1995. Salinity tolerance of rice (Oryza sativa L.) with reference to endogenous and exogenous abscisic acid. J. Agronomy and Crop Science, 174: 79-86.

Bond, J.W., 1994. How the World Bank and the EC policies are destroying the world environment. AgBé Publishing, Alkmaar, 152 pp.

Bouma, J., 1989. Using soil survey data for quantitative land evaluation. In: Stewart, B.A.(Ed.), Advances in Soil Science, Vol. 9. Springer-Verslag, New-York, pp. 177-213.

Bouma, J., Wopereis, M.C.S., Wösten, J.H.M. and Stein, A., 1993. Soil data for crop-soil models. In: Penning de Vries, F.W.T., Teng, P., Metselaar, K., Eds., Systems Approaches for Agricultural Development. Kluwer Academic Publishers, Dordrecht, pp. 207-220.

Bouman, B.A.M., 1994. A framework to deal with uncertainty in soil and management parameters in crop yield simulation: a case study for rice. Agricultural Systems, 46(1): 1-17.

Bouman, B.A.M., 1995. Crop modeling and remote sensing for yield prediction. Neth. J. Agr. Sci., 43: 143-161.

Bouman, B.A.M., Kasteren, H.W.J. and Uenk, D., 1992. Standard relations to estimate ground cover and LAI of agricultural crops from reflectance measurements. Eur. J. Agr., 1: 249-262.

Bregt, A.K., 1992. Processing of soil survey data. PhD thesis, Wageningen Agricultural University, Wageningen, 167 pp.

Bunnik, N.J.J., 1984. Review of models and measurements of multispectral reflectance by plant canopies. Recommendations for future research. Publication NLR MP 84039 U, Wageningen, 11 pp.

Caballero i Lluch, J.V., 1992. L'arròs en el Delta de l'Ebre: resultats dels assaigs 1979-1990. Departament d'Agricultura Ramaderia i Pesca, Generalitat de Catalunya. Fundació "la Caixa", Barcelona.

Canicio, A., 1996. Estudi sobre els processos regressius al Delta de l'Ebre: fenòmens de polderització de la plana deltaica -diagnosi i alternatives de gestió-. Departament de Medi Ambient (Generalitat de Catalunya), D.G. de Patrimoni Natural i Medi Físic, Report number 104, Barcelona.

Casanova, D., 1993. A remote sensing oriented study of the Ebro Delta (Spain). MSc thesis, Dept. of Soil Science and Geology, Wageningen Agricultural University, Wageningen, 39 pp.

Catalá Forner, M.M. and Fosch, T., 1997. Estudio de los factores que inciden en el rendimiento del arroz en el Delta del Ebro (Study of the factors that influence rice production in the Ebro Delta). Agrícola Vergel, Marzo: 120-128.

CBDSA, 1983. SINEDARES, Manual para la descripción codificada de suelos en campo. Ministerio de Agricultural Pesca y Alimentación, Madrid, 137 pp.

Ceuppens, J., Wopereis, M.C.S. and Miezan, K.M., 1997. Soil salinization processes in rice irrigation schemes in the Senegal river Delta. Soil Sci. Soc. Am. J., 61: 1122-1130.

Charles-Edwards, D.A., 1984. On the ordered development of plants 1. An hypothesis. Ann. Bot., 53: 699-707.

Chataignier, J., 1994. Rice in the mediterranean region. Medoryzae, 9: Sept.

Childs, C.W., 1981. Field test for ferrous ion and ferric-organic complexes (on exchange sites or in water-soluble forms) in soils. Australian Journal of Soil Research, 19: 175-180.

Christensen, S. and Goudriaan, J., 1993. Deriving light interception and biomass from spectral reflectance ratio. Remote Sens. Environ., 43: 87-95.

Clevers, J.P.G.W., 1989. The application of a weighted infrared-red vegetation index for estimating leaf area index by correcting soil moisture. Remote Sens. Environ., 29: 25-37.

Clevers, J.G.P.W., Verhoef, W., Buiten, H.J., Leeuwen, H.J.C., Maren, C., Varekamp, C. and Rijckenberg, G.J., 1991. Modelling and synergetic use of optical and microwave remote sensing. Report 2, LAI estimation from canopy reflectance and WDVI: a sensitivity analysis with the SAIL model. BCRS report number 90-39, 70 pp.

Connover, W.J., 1980. Practical nonparametric statistics. 2nd ed. John Wiley and Sons, New York.

Consorci d'Aigües de Tarragona, 1991. Planta de Tractament. Memòria de resultats 1989 i 1990. Control aigüa prepotable, potable i tractament.

Cook, M.G. and Evans, L.T., 1983. Nutrient response of seedlings of wild and cultivated Oryza species. Field Crops Research, 6: 205-218.

Cook, P.G. and Walker, G.R., 1992. Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. Soil Sci. Soc. Am. J., 56: 1015-1022.

Corwin, D.L. and Rhoades, J.D., 1982. An improved technique for determining soil electrical conductivity-Depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J., 46: 517-520.

CROPSCAN Inc., 1993. Multispectral Radiometer (MSR): User's manual and technical reference. CROPSCAN Inc., Rochester.

Custodio, E. and Llamas, M.R., 1983. Hidrología Subterránea. Ediciones Omega, Barcelona, 2 vols. 1-2350.

Daniels, R.B. and Hammer, R.D., 1986. Soil Geomorphology. John Wiley and Sons Ltd., New York.

De Datta, S.K., 1981. Principles and practices of rice production. John Wiley and Sons, Singapore.

De Datta, S.K., Gomez, K.A. and Descalsota, J.P., 1988. Data on rice yield and soil fertility parameters from long-term trials, under intensive rice cropping. Soil Science, 146(5): 350-358.

Decagon Devices, Inc., 1989. Sunfleck Ceptometer User's Manual. Decagon Devices Inc., Pullman.

Díaz, L. and Herrero, J., 1992. Salinity estimates in irrigated soils using electromagnetic induction. Soil Science, 154 (2): 151-157.

Dingkuhn, M., Penning de Vries, F.W.T., De Datta, S.K. and Van Laar, H.H., 1991a. Concepts for a new plant type for direct seeded flooded tropical rice. In: Direct seeded flooded rice in the tropics, pp. 17-38. International Rice Research Institute, Manila.

Dingkuhn, M., Schnier, H.F., De Datta, S.K., Dörffling, K. and Javellana, C., 1991b. Relationships between ripening-phase productivity and crop duration, canopy photosynthesis and senescence in transplanted and direct-seeded lowland rice. Field Crops Research, 26: 327-345.

Dobermann, A., 1994. Factors causing field variation of direct-seeded flooded rice. Geoderma, 62(1-3): 125-150.

Dobermann, A., Cassman, K.G., Sta Cruz, P.C., Adviento, M.A.A. and Pampolino, M.F., 1996. Fertilizer inputs, nutrients balance and soil nutrient supplying power in intensive, irrigated rice systems. III. Phosphorous. Nutrient Cycling in Agroecosystems, 46(2): 111-125.

Doi, K., Manabe, H., Sato, H. and Chigura, S., 1988. Cultivation techniques by direct under ground sowing method of rice plant in submerged paddy fields and water management. Fakukoka ken Nogyo Sogo Shikenjo kenkyu Hokoku, A. Sakumotsu. Fakukoka Agric. Res. Cent., Fakukoka, Jpn., 7: 25-80.

Dubey, S.K., Mondal, R.C. and Swarup, A., 1987. Effect of gypsum and pyrite with different moisture regimes on sodic soil improvement and rice yield. International Rice Research Newsletter, 12 (6): 35.

Duke, C., 1997. Assimilation de données de réflectance dans un modèle de fonctionnement de la betterave sucrière en vue de la prévision des rendements à l'échelle régionale. PhD thesis, INA-PG/INRA, Paris-Grignon.

Ehleringer, J. and Pearcy, R.W., 1983. Variation in quantum yield for CO_2 uptake among C3 and C4 plants. Plant Physiol., 73: 555-559.

FAO, 1995. FAO Yearbook 48; 1994, FAO Statistics Series no. 114, Rome.

Faure, J. and Mazaud, F., 1995. Rice quality in the European Union. Agriculture et développement, Dec., pp. 2-12.

Foody, G.M. and Curran, P.J., 1994. Environmental remote sensing from regional to global scales. John Wiley and Sons Ltd, Chichester, 278 pp.

Forno, D.A., Yoshida, S. and Asher, C.J., 1975. Zinc deficiency in rice. I. Soil factors associated with the deficiency. Plant and Soil, 42: 537-550.

Gao, L.Z., Jin, Z.Q., Huang, Y. and Zhang, L.Z., 1992. Rice clock model -a computer model to simulate rice development-. Agric. Forest. Meteor., 60: 1-16.

Gilabert, M.A. and Melià, J., 1990. Usefulness of the temporal analysis and the normalized difference in the study of rice by means of Landsat-5 TM images: Establishment of relationships for yield prediction purpose. Geocarto International, 5(4): 27-32.

Girdhar, I.K., 1988. Effect of saline irrigation water on the growth, yield and chemical composition of rice crop grown in a saline soil. J. Indian Soc. Soil Sci., 36: 324-329.

Gomez, K.A. and Gomez, A.A., 1984. Statistical procedures for agricultural research. 2nd Ed., John Wiley and Sons, New York.

Goudriaan, J., 1977. Crop micrometeorology: a simulation study. Simulation Monographs, PUDOC, Wageningen, 257 pp.

Goudriaan, J. and Van Laar, H.H., 1994. Modelling potential crop growth processes: textbook with exercises. Kluwer Academic Publishers, Dordrecht, 238 pp.

Graf, B., Gutierrez, A.P., Rakotobe, O., Zahner, P. and Delucchi, V., 1990. A simulation model for the dynamics of rice growth and development: Part I-The carbon balance. Agricultural Systems, 32: 341-365.

Greenwood, D.J., Neeteson, J.J. and Draycott, A., 1986. An analysis of the dependence of yields of potatoes and vegetable crops on soil properties and weather conditions. Jour. Sci. Food Agric., 37(7): 674-675.

Guillén, J. and Palanques, A., 1992. Sediment dynamics and hydrodynamics in the lower course of a river highly regulated by dams: the Ebro river. Sedimentology, 39: 567-579.

Habibullah, A.K.M., Rahman, S.M., Ali, M.I., Enayetullah, M., Hussain, K.M.M. and Biswas, M.R., 1977. Studies on the influence of drainage as a cultural practice in increasing rice yields. Curr. Sci., 46(14):469-471.

Hendrickx, J.M.H., Baerends, B., Raza, Z.I., Sadig, M. and Akram Chaudhry, M., 1992. Soil salinity assessment by electromagnetic induction of irrigated land. Soil Sci. Soc. Am. J., 56: 1933-1941.

Hill, J.E., Bayer, D.E., Bocchi, S. and Clampett, W.S., 1991. Direct seeded rice in the temperate climates of Australia, Italy, and the United States. In: Direct seeded flooded rice in the tropics, pp. 91-102. International Rice Research Institute, Manila.

Horie, T., Yajima, M. and Nakagawa, H., 1992. Yield forecasting. Agricultural Systems, 40: 211-236.

Horie, T., Ohnishi, M., Angus, J.F., Lewin, L.G., Tsukaguchi, T. and Matano, T., 1997. Physiological characteristics of high-yielding rice inferred from cross-location experiments. Field Crops Res., 52: 55-67.

Hseu, Z.Y. and Chen, Z.S., 1996. Saturation, reduction and redox morphology of seasonally flooded Alfisols in Taiwan. Soil Sci. Am. J., 60: 941-949.

Hsiao, T.C., 1993. Growth and productivity of crops in relation to water status. Acta Horticultura (Irrigation of Horticultural Crops), 335: 137-148.

Huang, Z.W. and Broadbent, F.E., 1988. The efficiency of potassium nitrate and urea fertilizers on rice in flooded soil. Soil-Science, 146 (6): 461-465.

Hutchinson, M.F., 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology, 106: 211-232.

Ibàñez, C., Rodrigues-Castillo, A. and Prat, N., 1995. The combined impacts of river regulation and eutrophication on the dynamics of the salt wedge and the ecology of the lower Ebro river (north-east Spain). In: Harper, D.M., Ferguson, A.J.D. (Eds.), The Ecological basis for river management, pp. 105-114. John Wiley and Sons Ltd, Chichester.

Ibàñez, C., Canicio, A., Day, J.W. and Curcó, A., 1997. Morphological development, relative sea level rise and sustainable management of water and sediment in the Ebre Delta, Spain. Journal of Coastal Conservation, 3: 191-202.

ICC, 1992. Ortofotomapas de Catalunya, 1:25.000. Sheets 522 (1-2, 2-1, 2-2) and 523 (2-1). Institut Cartogràfic de Catalunya, Barcelona.

IGME, 1979. Geologic map of Spain at 1:50.000. Sheets number 522 and 523. Instituto Geológico y Minero de España, Madrid.

Ishida, T. and Ando, H., 1994. Computer assisted mapping of paddy-field soils: II. Classification, mapping, and significance. Soil Sci. Plant Nut., 40(3): 403-414.

Ishiguro, E., Kumar, M.K., Hidaka, Y., Yoshida, S., Sato, M., Miyazato, M. and Chen, J.Y., 1993. Use of rice response characteristics in area estimation by LANDSAT/TM and MOS-1 satellites data. ISPRS J. Photogram., 48(1): 26-32.

Iwasaki, Y., Mae, T., Makino, A., Ohira, K. and Ojima, K., 1992. Nitrogen accumulation in the inferior spikelet of rice ear during ripening. Soil Sci. Plant Nutr., 38(3): 517-525.

Jiménez, J.A. and Sánchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro Delta. Marine Geology, 114: 105-118.

Jugsujind, A. and Patrick, W.H., 1977. Growth and nutrient uptake by rice in a flooded soil under controlled aerobic-anaerobic and pH conditions. Agron. J., 69: 705-710.

Kant, S. and Kumar, R., 1992. Effect of gypsum, pyrite, pressmud and farmyard manure on soil properties and yield of rice (Oryza sativa). Indian Journal of Agricultural Sciences, 62(3): 191-195.

Keulen, H. Van, and Seligman, N.G., 1987. Simulation of water use, nitrogen and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen, 310 pp.

Khan, H.R., Faiz, S.M.A., Islam, M.N., Adachi, T. and Ahmed, I.U., 1992a. Effects of salinity, gypsum and Zn of mineral nutrition of rice. Intern. J. Trop. Agric., 10(2): 147-156.

Khan, H.R., Yasmin, K.F., Adachi, T. and Ahmed, I.U., 1992b. Effects of gypsum, Zn and intermittent saline irrigation on the growth, yield and nutrition of rice plants grown in a saline soil. Intern. J. Trop. Agric., 38(3): 421-429.

King, D. and Le Bas, C., 1996. Towards a European soil information system: past activities and perspectives of the soil and GIS support group. In: Le Bas, C. and Jamagne, M., (Eds.). Soil databases to support sustainable development. INRA-SESCPF and JRC-IRSA, Orleans. pp. 115-124.

King, D., Daroussin, J. and Tavernier, R., 1994. Development of a soil geographical database from the soil map of the European Communities. Catena, 21: 37-56.

Kleinpenning, J.G.M., 1969. Geographical stability and Change in the Ebro Delta, Tijdschrift voor Econ. en Soc. Geografie, 60: 35-59.

Kogano, K., Toriyama, K. and Sekiya, H., 1991. Studies on nitrogen application on clayey gley paddy soil and very early drainage for rice. Bull. Hokuriku Natl. Agric. Exp. Stn., Joetsu, Kiigata, Jpn., 33: 107-125.

Kropff, M.J., van Laar, H.H. and Matthews, R.B., 1994. ORYZA1: an ecophysiological model for irrigated rice production. SARP Research Proceedings. DLO- Research Institute for Agrobiology and Soil Fertility, Wageningen, WAU-Department of Theoretical Production Ecology, Wageningen, and International Rice Research Institute, Manila, 110 pp.

Kwon, S.L., Smith, R.J. and Talbert, R.E., 1992. Comparative growth and development of Red Rice (*Oryza sativa*) and Rice (*O. sativa*). Weed Science, 40: 57-62.

Leblon, B., Guerif, M. and Baret, F., 1991. The use of remotely sensed data in estimation of PAR use efficiency and biomass production of flooded rice. Remote Sens. Environ., 38: 147-158.

Lesch, S.M., Rhoades, J.D., Lund, L.J. and Corwin, D.L., 1992. Mapping soil salinity using calibrated electromagnetic measurements. Soil Sci. Soc. Am. J., 56: 540-548.

Lewis, D.W. and MacConchie, D., 1994. Practical sedimentology. Chapman and Hall, New York.

Libes, S.M., 1992. An introduction to marine biogeochemistry. John Wiley and Sons, New York.

Liebig, J. Von, 1855. Principles of agricultural chemistry with special reference to the late researches made in England. 17-34. Reprinted in: Cycles of essential elements (Benchmark papers in Ecology Vol. I, L.R. Pomeroy (1974). Dowden, Hutchinson and Ross Inc., Stroudsburg, Pennsylvania, pp. 11-28.

Lin, C.F., 1984. Fertility Capability Classification as a guide to N fertilization of lowland rice. No. 27, 191-206 Taiwan Agric. Res. Inst., Taichung, Taiwan.

Loaso, C. and Herrán, F., 1989. Aportaciones al conocimiento de la hidroquímica e hidrología del acuífero del delta del Ebro. Su importancia en relación con el desarrollo de la acuicultura. IV Simposio de Hidrogeología, Palma de Mallorca.

López-Bruna, D. and Herrero, J., 1996. El comportamiento del sensor electromagnético y su calibración frente a la salinidad del suelo. Agronomie, 16: 95-105.

López Gutierrez, J.S., 1996. Recopilación y análisis de la información existente sobre el Delta del Ebro. Revista de Ingeniería de Civil. Madrid.

Magaldi, D., 1995. Soil mapping in EU countries: a short review. In: European land information systems for agro-environmental monitoring. CEC publication, JRC Ispra (I), pp. 171-186.

Maldonado, A., 1972. El Delta del Ebro; estudio sedimentológico y estratigráfico. PhD thesis, University of Barcelona (Faculty of Geology), Barcelona, 486 pp.

Maldonado, A., 1975. The Ebro Delta, sedimentary environments and development. In: IX International Congress of Sedimentology. Nice, France, pp. 19-58.

Maldonado, A. and Riba, O., 1971. El delta reciente del río Ebro: descripción de ambientes y evolución. Acta Geológica Hispánica, VI (5): 131-148.

MAPA, 1986. Métodos oficiales de análisis. Tomo III (Plantas, productos orgánicos fertilizantes, suelos, aguas, productos fitosanitarios, fertilizantes inorgánicos). Ministerio de Agricultura, Pesca y Alimentación, Madrid.

MAPA, 1995. Anuario de estadística agraria. Madrid.

Mathers, S.J. and Zalasiewicz, J.A., 1994. A guide to the sedimentology of unconsolidated sedimentary aquifers (UNSAs). British Geological Survey Technical Report WC/93/32, Robquestprint, Ashford.

Matsuo, T., Kumazawa, K., Ishii, R., Ishihara, K. and Hirata, H. (Eds.), 1995. Science of the rice plant, Vol. II, Rice physiology. Food and Agriculture Policy Research Center, Tokyo.

Matsushima, S., 1957. Analysis of developmental factors determining yield and yield prediction in lowland rice. Bull. Nat. Inst. Agric. Sci., A5: 1-271.

McCown, R.L., Hammer, G.L., Hargreaves, J.N.G., Holzworth, D.P. and Freebairn, D.M., 1996. APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems, 50 (3): 255-271.

Molenaar, M. and Richardson, D.E., 1994. Object hierarchies for liking aggregation levels in GIS. Proceedings Symp. of ISPRS, Comm. IV. Athens, Georgia.

Monsi, M. and Saeki, T., 1953. Über den Lichtfaktor in den Pflänzengesellschaften und seine Bedeutung für die Stoffproduktion. Jpn. J. Bot., 14: 22-52.

Monteith, J.L., 1973. Principles of Environmental Physics. Edward Arnold Limited, London.

Mookhoek, M., Berkhout, P. and Meester, G., 1992. De hervorming van het EG-landbouwbeleid. The reform of the CAP. Economisch Statistische-Berichten, 77 (3864): 588-592.

Moorman, F.R. and Van Breemen, N., 1978. Rice: soil, water and land. International Rice Research Institute, Manila.

Mouret, J.C., 1988. Etude de l'Agrosystème Rizicole en Camargue dans ses Rotations avec le Milieu et le Système Cultural: Aspects Particuliers de la Fertilité. PhD thesis, Inra-Lecsa, Montpellier, 191 pp.

Obermueller, A.J. and Mikkelsen, D.S., 1974. Effects of water management and soil aggregation of the growth and nutrient uptake of rice. Agron. J., 66: 627-632.

Patel, N.K., Singh, T.P., Sahai, B. and Patel, M.S., 1985. Spectral response of rice crop and its relation to yield and yield attributes. Int. J. Remote Sens., 6: 657-664.

Patrick, W.H., Mikkelsen, D.S. and Wells, B.R., 1985. Plant nutrient behaviour in flooded soil. In: Fertilizer Technology and Use, 3rd Edition. Soil Science Society of America, Madison WI, pp. 197-228.

Peng, S., Cassman, K.G. and Kropff, M.J., 1995. Relationship between leaf photosynthesis and nitrogen content of field-grown rice in the tropics. Crop Science, 35(6): 1627-1630.

Penning de Vries, F.W.T. and van Laar, H.H., 1982. Simulation of plant growth and crop production. Simulation Monographs, Pudoc, Wageningen.

Pons, L.J. and Zonneveld, I.S., 1965. Soil ripening and soil classification. Initial soil formation in alluvial deposits and a classification of the resulting soils. Inter. Inst. Land Reclam. and Impr., Pub. 13, Wageningen, 128 pp.

Porta, J. and Rodríguez-Ochoa, R., 1991. Translocaciones sólidas en suelos con características sódicas en Monegros-Flumen (Huesca): Procesos e implicaciones para el uso agrícola. Suelo y Planta, 1: 603-617.

Proyecto de saneamiento y riegos del Delta del Ebro, 1966. Informe tipo reconocimiento de la viabilidad técnica y económica del drenaje del Delta del Ebro y sustitución del cultivo del arroz por otros cultivos de regadío. Ministerio de Agricultura, Instituto Nacional de Colonización (Hydrotechnic Corporation, S.A.), Vol 2. Madrid.

Qadar, A., 1995. Potassium and sodium contents of shoot and laminae of rice cultivars and their sodicity tolerance. Journal of Plant Nutrition, 18(11): 2281-2290

Qi, M., 1987. A study on the abundance and deficiency of zinc in paddy soil in Anqing Prefecture and the effects of zinc fertilizer application. Journal of Soil Science, China, 18(5): 228-230.

Ramasamy, S., Berge, H.F.M. Ten, Purushothaman, S., 1997. Yield formation in rice in response to drainage and nitrogen application. Field Crops Res., 51:65-82.

Ribeiro, M.R., Halstead, E.H. and Jong, E. de, 1984. Rendimento da cana-de-acucar e caracteristicas das terras da microrregiao da mata norte de Pernambuco (Relationship between sugarcane yield and some land characteristics of the north forest zone of Pernambuco state, Brazil). Revista Brasilera de Ciencia do Solo, 8(2): 209-213.

Richards, L.A., 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60, U.S.D.A., Washington D.C..

Rodskjer, N., 1972. Measurements of solar radiation in barley and oats. Swed. J. Agr. Res., 2: 71-81.

Rouse, J.W. Jr., Haas, R.H., Schell, J.A. and Deering, D.W., 1973. Monitoring vegetation systems in the Great Plains with ERTS. Earth Res. Techn. Satellite-1 Symp., Goddard Space Flight Center. Washington D.C., pp. 309-317.

Russell, G., Jarvis, P. G. and Monteith, J.L., 1989. Absorption of radiation by canopies and stand growth. In: G. Russell, J. Marshall and P.G. Jarvis (Editors), Plant Canopies: Their Growth, Form and Function, pp. 21-41. Cambridge University Press, Cambridge.

Schumm, S.A., Mosley, M.P. and Weaver, W.E., 1987. Experimental fluvial geomorphology. John Wiley and Sons Ltd., New York.

Sharif Zia, M., Salim, M., Aslam, M., Gill, M.A. and Rahmatullah, S., 1994. Effect of low temperature of irrigation water on rice growth and nutrient uptake. J. Agronomy and Crop Science, 173: 22-31.

Shin, J.C., Lee, M.H. and Kim, J.K., 1994. Development of a model subroutine to describe tiller development in Korean rice. In: R.B. Matthews, M.J. Kropff, T.M. Thiyagarajan and A.A. Kareem (Eds.), The development, testing and application of crop models simulating the potential production of rice. SARP Research Proceedings. DLO-Research Institute for Agrobiology and Soil Fertility, Wageningen and IRRI, Manila.

Silva, J.A. (Ed.), 1985. Soil-based agrotechnology transfer. Benchmark Soils Project, Department of Agronomy and Soil Science, Hawaii Institute of Tropical Agriculture and Human Resources, College of Tropical Agriculture and Human Resouces, University of Hawaii, Hawaii.

Singh, Y., Khind, C.S. and Singh, B., 1991. Efficient management of leguminous green manures in wetland rice. Advances in Agronomy, 45: 135-189.

Slavich, P.G., 1990. Determining EC_a-depth profiles from electromagnetic induction measurements. Australian Journal of Soil Research, 28: 443-452.

Soga, Y. and Nozaki, M., 1957. Studies on the relation between seasonal changes of carbohydrates accumulated and the ripening at the stage of generative growth in rice plant. Proceedings of the Crop Science Society of Japan, 26: 105-108.

SSS, Soil Survey Staff, 1992. Keys to Soil Taxonomy (Fifth Edition). SMSS Tech. Man. 19, Blacksburg (Virginia).

SSS, Soil Survey Staff, 1996. Keys to Soil Taxonomy (Seventh Edition). USDA-NRCS. Pocahontas Press, Blacksburg (Virginia).

START, 1997. A joint START/WCRP/IGBP-GCTE Workshop on climate variability, agricultural productivity and food security in the Asian Monsoon Region. Manton, M., Phelan, A. and Virji, H. (Eds.). START Report 1997/2. Bogor, Indonesia 19-22 February 1997.

Stein, A., 1991. Spatial interpolation. PhD thesis, Wageningen Agricultural University, Wageningen, 263 pp.

Stein, A., Brouwer, J. and Bouma, J., 1997. Methods for comparing spatial variability patterns of millet yield and soil data. Soil Sci. Soc. Am. J., 61: 861-870.

Trangmar, B.B., Yost, R.S., Wade, M.K., Uehara, G. and Sudjadi, M., 1987. Spatial variation of soil properties and cleared land. Soil Sci. Soc. Am. J., 51(3): 668-674.

Um, M.H., Jung, P.K. and Im, J.N., 1995. Effects of percolation and soil amendments on the changes of physico-chemical properties and rice yield in paddy soil. RDA Journal of Agricultural Science, Soil and Fertilizer, 37(1): 264-270.

USDA, 1993. Soil survey manual. USDA handbook number 18. USDA, Washington.

Van Lanen, H.A.J., 1991. Qualitative and quantitative physical land evaluation: an operational approach. PhD thesis, Wageningen Agricultural University, Wageningen.

Watanabe, K., Fukuzawa, S., Higuchi, F., Saito, S. and Watanabe, S., 1974. Effect of percolation on the growth and grain yields of rice plant and physico-chemical properties of paddy soil. J. Sci. Soil Manure Jpn., 45(10): 441-446.

Webster, R. and Oliver, M.A., 1990. Statistical methods in soil and land resource survey. Oxford University Press, New York.

Wiegand, C.L. and Richardson, A.J., 1987. Spectral components analysis: rationale and results for three crops. Int. J. Remote Sens., 8(7): 1011-1032.

Williams, R.L., Durkin, C.O. and Stapper, M., 1994. A simple model of rice yield response to N fertiliser and it's use as a decision support system. In: E. Humphrets, E.A. Murray, W.S. Clampett and L.G. Lewin (Eds.), Temperate rice conference. Yanco Agricultural Institute, Yanco (New South Wales).

Wisiol, K., 1987. Choosing a basis for yield forecasts and estimates. In: K. Wisiol and J.D. Hesketh (Eds.), Plant growth modelling for resource management, Vol. 1, pp. 75-103. CRC press, NW.

Wollenhaupt, N.C., Richardson, J.L., Foss, J.E. and Doll, E.C., 1986. A rapid method for estimating weighted soil salinity from apparent soil electrical conductivity measured with an above-ground electromagnetic induction meter. Canadian Journal of Soil Science, 66: 315-321.

Yin, X., 1996. Quantifying the effects of temperature and photoperiod on phenological development to flowering in rice. PhD thesis, Wageningen Agricultural University, Wageningen, 173 pp.

Yoshida, S. and Tanaka, A., 1969. Zinc deficiency of the rice plant in calcareous soils. Soil Sci. Plant Nutr., 15: 75-80.

Yoshida, S., 1981. Fundamentals of rice crop science. International Rice Research Institute, Manila, 269 pp.

Younger, M.S., 1979. Handbook for linear regression. Duxbury press, N.S., Massachusetts.

Curriculum vitae

David Casanova was born on 29 December 1967 in Barcelona, Spain. He grew up in Tortosa (35 km inland of the Ebro river mouth) where his family was engaged in orange and rice farming. After spending one year of high-school in Spokane (USA), he moved to Barcelona where he graduated from high-school. He studied at the University Ramon Llull (Instituto Químico de Sarriá) where he graduated in 1991 as Industrial Engineer, with a specialization in Chemistry. He, then, shifted into "natural" sciences and enrolled at the MSc "Soil and Water" programme (1991/93) of the Wageningen Agricultural University. He had a fellowship from the Catalan Autonomous Government to study soil salinity and water management relations in the Ebro Delta. From 1993 to 1998, he has been conducting the study of soils, weather and rice described in this thesis. For this purpose he has been financed by the Commission of the European Communities and the Consejo Superior de Investigaciones Científicas (CSIC). During this period, he has worked at the department of Soil Science and Geology of the Wageningen Agricultural University and at the Institute of Earth Sciences "Jaume Almera" of the CSIC in Barcelona.

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