Soil potassium dynamics under intensive rice cropping.

A case study in the Mekong Delta, Vietnam.

Nguyen My Hoa

Promotor:	Prof. Dr. Ir. O. Oenema
	Hoogleraar, Management van Nutriënten en Bodemvruchtbaarheid
Copromotor:	Dr. Ir. B. H. Janssen
	Universitair Hoofddocent, sectie Bodemkwaliteit

Samenstelling promotie commissie

Prof. dr. A. Dobermann, University of Nebraska, Lincoln, NE, USA
Prof. dr. ir. R. Merckx, Katholieke Universiteit Leuven, België
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Dr. ir. M.E.F. van Mensvoort, Wageningen Universiteit

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Abstract

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Rice cropping has been greatly intensified in many Asian countries during the last decades to meet the increasing demand for food by the increasing population. There is some concern now that the increased crop yields and nutrient withdrawal, in combination with unbalanced fertilization, lead to potassium (K) depletion of the soil and to K deficiency in rice. However, reports about crop response to K fertilizer application in wetland rice cropping systems show conflicting results, and there are no proper guidelines for K management.

This study was set-up to increase the understanding of K budgets of rice cropping systems, and of K dynamics in soil, to be able to develop K management schemes for the various rice cropping systems. The study was carried out in the Mekong Delta of Vietnam, a major rice growing area. Field studies have been carried out to quantify the inputs and outputs of K in various rice cropping systems. Kinetics of K adsorption-desorption and of K fixation-release in soil has been studied in the laboratory to understand the behavior of K in soils. Pot experiments have been carried out to study effect of water management, K fertilizer application on soil K pools and K uptake, and examine the rate of changes of various K pools in soil by rice, grown under controlled conditions. Models were used to analyze and predict changes of K pools in soils over time, using rate constants and initial pool sizes as derived from the laboratory and pot experiments.

K budgets were assessed for areas, representing double and triple rice cropping systems on flooded alluvial soils. Partial K budgets proved inadequate and a differentiation between pools according to the availability of K in sediments was useful. K balances were always positive for total K, and negative for K(NH_4OAc) unless about 80 kg fertilizer K was applied, while balances for K(NaTPB) were in between. Removal of rice straw was the largest K output, sedimentation the largest input for total K.

The order of the amounts of extracted K was 0.01 M $CaCl_2$ < 1M NH_4OAc pH 7 < 1 M HNO_3 < 0.2 M NaTPB. All methods were well correlated with plant uptake of K. Simple first order equations adequately described adsorption, fastening and desorption of K. The rate coefficient of K removal with NaTPB decreased over time and could be accounted for by the Yang and Janssen equation.

In a greenhouse experiment, water management between two successive crops had no influence on soil K(NH_4OAc) and K(NaTPB), and on K uptake. Because K(NaTPB) did not decrease over time, it was concluded that the intermediate pool in a three-pools model could not be assessed by K(NaTPB). Hence the test of a three-pools model failed.

Two models were tested using the results of greenhouse experiments. A so-called Series model, in which K flows from minerals to an intermediate pool, next to the labile pool of exchangeable K according to first-order kinetics was able to predict the dynamics of soil K pools over time and K uptake in the future. Also a reduced Series model with only two pools was well applicable. The so-called Parallel model in which K moves from each of the pools to the solution pool turned out to be useful for a first interpretation of experimental data to identify the sources of K uptake, but it was unable to predict future soil K changes and hence future K uptake. The Parallel model was useful to identify the source of K uptake, but not to predict future soil K changes and K uptake. Based on application of the Series model, a decision support system scheme on soil K management was outlined.

Key words: potassium, nutrient budgets, nutrient depletion, fertilizer, kinetics, adsorption, desorption, fixation, release, modeling, rice cropping system, NaTPB-extractable K, NH_4OAc-extractable K, sedimentation.

Preface

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This thesis is dedicated to my parents and my family

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Abstract

CHAPTER 1:

POTASSIUM, RICE PRODUCTION AND THE MEKONG DELTA

1.1. Intensification of crop production and potassium in Asia

As the word population is still increasing and will be about 8.3 billion by 2025, and expansion of arable land is hardly realistic in densely populated Asia, crop intensification is often the main vehicle for increasing food output (e.g. Cassman et al., 2003). Rice is the staple food of billions of people in Asia, and rice cropping was indeed intensified in many Asian countries during the last 30 years of the 20th century. This intensification of crop production, in combination with unbalanced fertilization, has resulted in depletion of potassium (K) in soils over large areas in China (Jiyun et al. 1999), India (Hasan, 2002) and other countries in South-East Asia (Dobermann et al., 1996b, 1998).

According to Jiyun et al. (1999), high-yielding crop varieties and improvements in farming practice, together with fertilizer nitrogen (N) application, have increased crop yield in China significantly in the 1960s. At the same time, soils were depleted in plants nutrients (except N). Phosphorus (P) turned out to be the next most deficient plant nutrient, and became a yield-limiting factor. Hence, P fertilizer application became an important measure for further increases in crop yield. From the early 1970s onwards, with continuous increases in crop yield through increased use of N and P fertilizers, K deficiency was observed, first in southern China, but it has gradually extended to the north of China. Between 1950 and 1980, fertilizer use in China was far from balanced, with relatively more N used than P and K. Though the situation has slowly improved from the late 1980s onwards, fertilizer use in China is still not well balanced at present, with relatively less use of P and K fertilizers relative to N fertilizers. Because of the inadequate addition of K fertilizer and substantial removal of straw from the field, soil K depletion has continued, causing rapid expansion of K deficient areas and locally significant responses of crop yield to K fertilization (Jiyun et al., 1999).

Similar increases in soil K depletion have been observed in India. The categories of low and high levels of available K in soils of India have decreased by 0.6 and 6.4%, respectively, while the area of the medium category increased by 7% (Hasan, 2002), relative to data presented by Ghosh and Hasan (1980). This reflects that K fertilizers were scantily applied in the last two decades (Hasan, 2002).

In South and Southeast Asia, K deficiency typically occurs in highly weathered soils (Oxisols, Ultisols) and coarse-textured soils (Dobermann et al., 1998). Most soils of the great alluvial floodplains in Asia were generally regarded as high in extractable K, and it was thought that additional K supply from irrigation water would make K a rare limiting factor in irrigated rice systems (Kawaguchi and Kyuma, 1977; De Datta and Mikkelsen, 1985; Bajya, 1994). But K deficiency is now widespread even on heavy-textured soils including alluvial, illitic soils in India (Tiwari, 1985), lowland rice soils of Java (Sri Adiningsih et al., 1991), and vermiculitic clay soils of central Luzon, Phillipines (Oberthuer et al., 1995). Indigenous supplies of K were found low in plots where K additions were withheld (zero K plots) in the Mekong Delta-Vietnam (O Mon site) and in Indonesia (Dobermann et al., 2003).

In the Mekong Delta in Vietnam, rice cropping becomes more and more intensive while little K fertilizer has been applied in the past. Deficiency of K in rice growing in the Mekong Delta is not yet widespread, but the K deficiency problems that farmers in China and India have encountered, concern researchers and policy makers in Vietnam, especially in The Mekong Delta.

Evidently, management of K has become now very important in sustaining or increasing crop yield in Asia. Proper K management requires a thorough understanding of soil K behavior and of the various K inputs and outputs of cropping systems. It is well-known that the availability of K to plants does not only depend on the size of the available pool in soil, but also on the transport of K from soil solution to the root zone and from the root zone into plant roots (e.g. Barber, 1985). Many plant factors (variety, root system, and antagonistic and synergistic mechanisms in ion uptake), soil factors (pH, organic matter content, texture, complementary cations) and environmental factors (rainfall, temperature) may affect these processes. However, when plant available soil K is sufficient, these factors tend to become less important. Therefore maintenance of soil K is a key factor to sustain and increase crop yields.

1.2. The Mekong Delta of Vietnam

1.2.1. Location and climate

The Mekong Delta (MD) in Vietnam is a major rice growing area in Southeast Asia. It covers an area of 3.9 millions ha, between longitudes 104^o 30’ to 107^{o}E and latitudes 8^{o}30’ to 11^{o}N. There are 12 provinces located in the delta: Long An, Tien Giang, Ben Tre, Vinh Long, Tra Vinh, An Giang, Dong Thap, Kien Giang, Can Tho, Soc Trang, Bac Lieu, Ca Mau (Fig.1.1).

Except for hill areas in Kien Giang and An Giang, where hard rock is exposed, the Mekong Delta is a flat and low-lying area. The average altitude of the delta is about 2 meters above mean sea level (MSL). Lowest areas are in Dong Thap province with an altitude of 0.5 m below MSL (Tran Kim Thach, 1983, as cited by Danida project, 1995).

The Delta has a monsoon tropical semi-equatorial climate, with a mean temperature of about 25 to 28^o C. During the coolest months (December and January), the mean temperature is 23 to 25^o C and during the warmest months (March and April) it is 32 to 33^o C (Phong, 1986).

The mean annual rainfall is about 1600 mm for the whole Delta. In the Western part, rainfall is up to 2000-2500 mm; in the central part it is 1200-1500 mm, and towards the eastern part, it is 1500-1600 mm. There are two distinct seasons: the rainy season from May to November with about 90% of the total annual rainfall, and the dry season from December to April with a rainfall of about 10% of the total annual amount (Phong et al., 1986).

1.2.2. Hydrology and flood characteristics

The Mekong river is the largest river in Southeast Asia with a length of 4200 km, passing through China, Myanmar, Thailand, Laos, Cambodia, and Vietnam. Its total watershed covers an area of 795000 km^2, of which the MD in Vietnam occupies 39000 km^2 (5% of the total watershed area). At Phnom Penh (Cambodia), the Mekong river meets the Tonle Sap and then branches into the Tien Giang and Hau Giang rivers before entering Vietnam. The Tien Giang itself branches into five tributaries, and the Hau Giang branches into four tributaries. Moreover, the Delta has other important rivers such as Vam Co Dong, Vam Co Tay, Cai Lon, Ong Doc, Trem, and My Thanh.

Upstream, the Delta is influenced by rivers, and downstream by the diurnal tidal movements of the Eastern Sea and the semi-diurnal tidal movement of the Western Sea. The annual rainfall combined with the high level of the Mekong River results in regular floods of 0.3 to 3 m during the wet season, mainly from August to November (with highest flood in September). The entire area is dry during the dry season (December to April). When the river flow is reduced, salt water intrudes the inland, especially in April and early May, affecting 2.1 millions ha in the coastal area (Ministry of Water Resource, 1994).

The flooded areas in the Delta occupy 1.9 millions ha, including areas in Dong Thap, Long An, Tien Giang, Ben Tre, Vinh Long, An Giang, Kien Giang and Can Tho. In general, the altitude decreases from the North to the South. The Plain of Reeds region - a low floodplain which includes parts of Long An and Dong Thap - is a closed flooding area, while the Long Xuyen quadrangle (parts of An Giang and Kien Giang) is an open flood plain.

With many natural streams and a dense network of man-made canals, the Mekong Delta has a complex hydraulic regime and an annual flood season. The annual flood is influenced by the upstream flood of the Mekong river, rain inland, river networks and road systems of the area, of which the main determinant factor is the upstream flood.

The flood intrudes the Delta from two directions: (a) from the flooded area in Cambodia (10-15% of the total amount) with low sediment in the water and (b) from the Tien Giang and Hau Giang rivers (85-90 % of the total flood), which is rich in sediment. Flood flows from flooded areas in Cambodia intrudes most of the Plain of Reeds. The other sources of flood in this area are from the Tien Giang River and from local rainfall.

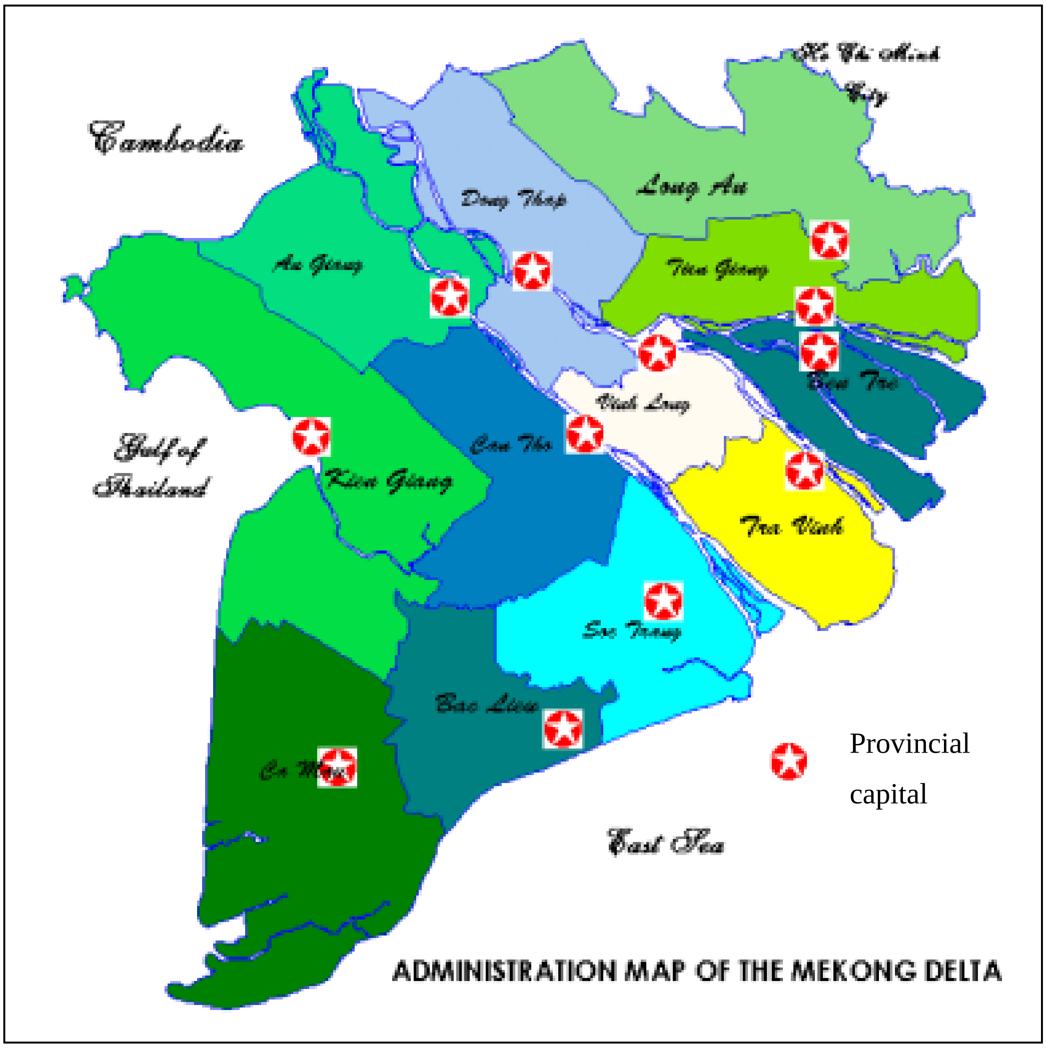

Figure 1.1: Administration map of the Mekong Delta, Vietnam.

The flood that intrudes the Long Xuyen quadrangle comes partially from the Mekong river (which has passed through Cambodia), partially from the Hau Giang river and partially from local rainfall. This flood flows to the West, to the Rach Soi river in Kien Giang and the Hau Giang river.

According to Truong (1998), flood intrusion from Cambodia to the Plain of Reeds and the Long Xuyen Quadrangle has increased during the past 40 years, thereby depressing the flow from the Tien Giang and Hau Giang rivers, which then has resulted in less sediment deposition in these areas.

1.2.3. Soils in the Mekong Delta

The Mekong Delta is a young landmass formed not more than 10,000 years ago. At the end of the Pleistocene, the delta was a mass of muddy land and the sea level was lower than at present. At the beginning of the Holocene, the sea level rose, and marine sediments of different thickness were deposited. The sediment layers are 8 m and 6 m thick in Can Tho and Cai Lay, respectively (Phong, 1986). In Moc Hoa, this sediment is not found because the sea level was not high enough for this region. Therefore, only old-alluvial soils are found in these areas.

When the sea withdrew from the Delta, sediment from the Mekong River was deposited. The present delta consists of levees, floodplains and sandbars parallel to the coastline. Between the sandbars, ancient mangrove forests have added organic matter to both fluviatile and marine sediments, providing ideal conditions for the formation of the acid sulfate soils. The combined action of the river and the sea has formed good alluvial soils along the river and acid sulfate soils in backswamps. The final step of delta formation process was the formation of coastal areas.

According to Chieu et al. (1990), the MD soils can be divided into seven groups (Table 1.1):

- Alluvial soils along the Mekong river. These are the most productive soils for rice and fruit growing in the MD.

Table 1.1: Major soil groups in the Mekong Delta.

Soil group	USDA classification	FAO/UNESCO Classification	Area (ha)	% of total area
1. Alluvial soils			1,184,857	31.5
Tidal flat alluvial soil	- Fluvaquents - Ustifluvents	- Fluvisols		
Developed alluvial soils	- Ustropepts - Tropapepts	- Gleysols		
2. Acid Sulfate soils (ASS)			1,000,263	26.8
Shallow potential ASS	Sulfaquents	Sulfi Thionic Fluvisols		
Moderate potential ASS	Sulfic Tropaquents Pale Sulfic Tropaquents	Sulfi Thionic Fluvisols		
Extensive actual ASS	Sulfaquepts	Orthi thionic Fuluvisols		
Moderate actual ASS	Sulfic Tropaquepts Pale -Sulfic-Tropaquepts	Orthi thionic Fuluvisols		
3. Saline Acid sulfate soils			662,285	17.2
Saline Shallow potential ASS	Sulfaquents - Salic	Sali- Sulfi- Thionic-Fluvisols		
Saline moderate potential ASS	Sulfic-Tropaquepts-Salic-Sulfic -Tropaquents-Salic	Sali- Sulfi- Thionic-Fluvisols		
Saline Extremely actual ASS	Sulfaquepts - Salic	Sali- Orthi Thionic Fluvisols		
Saline-moderately actual ASS	Sulfic-Tropaquepts-Salic-Pale-Sulfic Tropaqepts-Salic	Sali- Orthi Thionic Fluvisols		
4. Peaty acid sulfate soils	Sulfihemist-Sufohemist	Thionic-Histosols	24,027	0.7
5. Saline soils			682.262	18.3
Pemanently saline soil	Salic Hydraquents Salic Haplaquents	Gleyic Solonchaks		
Strongly Saline soil	Salic Fluvaquents Salic Ustiflents	Stagni Salic Fluvisols		
Slightly saline soil	Tropaquepts Salic Ustopoquepts Salic	Stagni Salic Fluvisols		
6. Grey soil and others	Tropaquults	Acrisols	145,763	4.0
7. Sandy Soils	Fluventic tropapsamments	Hpalic Arensols	43,318	1.5
Total			3,742,775	100

Source: Ton That Chieu et al., 1990

- Acid sulfate soils in the most depressed areas (backswamps), far from the river, where they were not covered by river sediment or only with a thin layer. This soil group originated from the old saline backswamps, and can be further divided in 5 types of acid sulfate soils: actual and potential acid sulfate soils with and without saline intrusion, and peaty acid sulfate soil

- Saline intruded soils along the coast from the eastern to the western part. This group may be divided into two subgroups: dry season saline soils and permanent saline soils. These soils are fertile but the salinity limits plant growth.

- Grey soils, occupying a small area in the delta, but playing an important role in land resources of some provinces. They are divided into two groups: soils developed on acid magmatic rocks and soils developed on old alluvial deposits. Nutrients are low in these soils, especially phosphorus and potassium.

- Sand ridge soils, distributed along the Eastern coast. Rice and upland crops are cultivated on these soils. The position on the sandbar or between sandbars dictates the texture of the soil.

1.3. Rice production and fertiliser use in the Mekong Delta

The Mekong Delta is a major rice-growing region in Vietnam and also in Southeast Asia. The cultivated area amounts to 2.79 millions ha (71.6% of the total area). More than 90% of this cultivated area is used for rice production (National Institute of Agriculture, Planning and Projection, 2000), providing more than 50 % of the national food requirement.

1.3.1.The irrigated rice cropping system

According to Tan et al. (2003), rice production in the MD has changed rapidly during the past three decades. Before 1975, local rice varieties with long growth duration

(180-200 days) covered most of the rice area and only one crop per year was grown. During 1975-1980, high-yielding, semi-dwarf rice varieties requiring less than 150 days were introduced and gradually replaced the local rice varieties. Between 1980 and 1990, improved irrigation systems were developed and double cropping of rice became common. During 1990 to 1995, short duration varieties (~100 d) were released and rapidly adopted by farmers. Since 1995, several varieties with ultra-short duration (85-90 d) were released to meet the requirements of triple-crop systems with minimum land preparation. In the past 10 years, many farmers have moved to systems in which three crops are grown per year, and even to seven rice crops per two years in some areas. The area under triple cropping increased from about 75,000 ha in the early 1990s to about 400,000 ha in 2000, although the government has tried to discourage farmers from doing so. In a triple crop system, farmers usually harvest 12 to 15 Mg rice ha^{-1} yr^{-1}. Triple rice produces 1.0-1.5 Mg ha^{-1} more than double rice, but the profit from double and triple cropping systems is almost the same. Farmers grow three rice crops per year because they have a more steady cash flow, and they can use family labor.

The rice crops are classified according to their period of cultivation. Planting date of each crop in each system is shifted depending on local conditions. In double crop systems, there are two main crops, the Winter-Spring crop (or the dry season crop) from November/December to February/March and the Summer-Autumn crop (or the wet season crop) from April/May to July/August. In triple crop systems, depending on the area, the extra crop can be a Spring-Summer crop (early wet season crop) or an Autumn-Winter crop (late wet season crop). In areas where irrigation is sufficient in the dry season, the extra crop will be the early wet crop from March to May, and the wet crop will be grown from May to July. However, in areas where irrigation is not sufficient during the dry period and the flood arrives late, the wet season crop will be from April to June followed by a late wet season crop from June/July to August/September. In areas with flooding, the late wet crop has to be planned in such a way that the crop is harvested before the flood arrives in September. At the beginning of the dry season crop, pumps are sometimes used to drain the fields to allow for earlier sowing. In triple crop systems, complete land preparation, including plowing, harrowing, puddling is done only once a year after the dry season crop. For the other crops, farmers may harrow or just puddle the soil and broadcast seeds for the next crop. In double crop systems, land preparation for the wet season crop can be done on dry land or wet land during the low flow period. For the late wet season crop, the land is prepared by puddling or by rotary cultivator.

The yield potential of rice is highest in dry season crops. Dry season rice can yield up to 7 or 8 Mg ha^{-1} with very good management, whereas wet season yields hardly exceed 5 Mg ha^{-1}. The dry season is favorable for growing rice due to the sunny weather. Wet season crops face many problems. Drought often affects the early wet season crop, whereas floods cause damage to the late wet season crop. In wet season crops, weeds, diseases and insect pests are common and cloudy weather also limits yields. Therefore, average wet season yields are only around 3.5 Mg ha^{-1} while average dry season yields are about 6 Mg ha^{-1} (Tan et al., 2003).

1.3.2.Fertilizer use

Before high-yielding rice varieties were introduced in 1967, most of the cultivated areas of the Delta were planted to local, late maturing rice varieties with tall plants and low yields. Traditional transplanting of single rice seedlings was used. Since 1960, farmers in the Mekong Delta started to use chemical fertiliser, mainly N fertiliser. Nitrogen had become the first limiting factor for rice and other crops. Phosphorus (P) fertiliser was not used by farmers at that time (Thuan and Bo, 2001).

The introduction of high yielding rice varieties around 1967 has improved the use efficiency of N fertiliser and increased rice yields significantly. During the 1970’s, many studies showed that P evolved as the next limiting factor in soils, and the use of P fertiliser increased from 1980 onwards (Thuan and Bo, 2001). Since the introduction of triple rice cropping in about 1986, farmers increased the use of fertilisers, especially N and P, but they continued to apply little or no K.

Progressive farmers follow the existing fertilizer recommendations, but most farmers follow their own experiences. The amounts of N, P and K applied are often unbalanced. A survey among 24 farmers in the O Mon district showed that application rates were about 100 kg N and 20 kg P ha^{-1} per crop in both the dry and wet season, although yields are much lower in the wet season than in dry season. Application of K was not common, on average about 10 kg K ha $^{-1}$ per crop (Tan et al., 2003). Farmers usually split applied N fertilizers in three to four doses, while P and K fertilizers are applied once or split over two applications, mostly starting about two weeks after sowing.

After the introduction of NPK compound fertilisers to the Vietnamese market around 1990, small amounts of K have been added to the soil through these fertilisers. Surveys conducted in the Mekong Delta suggest that either no K is applied or only 7-25 kg K ha$^{–1}$ per rice crop on alluvial soils. For comparison, surveys conducted in other rice-growing regions of Asia suggest an average use of 18 kg K ha$^{–1}$ per crop (Dobermann & Cassman, 1997), varying from zero in Thailand to more than 60 kg K ha$^{–1}$ in Southeast China and the Red River Delta of North Vietnam (Moya et al., 2003). In Vietnam, the use of NPK-fertilisers is increasing nowadays (Table 1.2). In recent years, many farmers started to use fluid fertilizers containing some NPK plus micronutrients, often mixed with fungicides, for foliar application.

Table 1.2: Fertiliser consumption in Vietnam in the period 1990-2000. (Source: Thuan and Bo, 2001)

Year	N Gg	P Gg	K Gg	Cultivated area, 1000 ha	NPK-fertilizer, Kg ha^{-1}
1990	451	23.8	20.4	9040	54.8
1991	656	65.0	14.2	9409	78.1
1992	573	81.9	36.9	9752	71.0
1993	566	66.7	17.3	9979	65.1
1994	736	112.8	60.0	10172	89.4
1995	747	149.1	77.3	10497	92.7
1996	1026	188.5	120.9	10929	122.2
1997	888	159.5	133.1	11316	104.3
1998	1064	176.4	173.5	11730	120.6
1999	1068	221.0	387.7	12320	136.1
2000	1031	206.8	204.0	12278	117.4

1.3.3. Response of rice to potassium application

1.3.3.1. On- farm trials conducted by Can Tho University

Early field experiments conducted by Xuan and Hiep (1970) showed that there was no response of rice to K fertilizer application on alluvial soils of the Mekong Delta. Ren and Hoa (1993) also found that rice did not respond to K application on such soils. In these experiments, K additions were 0 and 30 kg ha^{-1} and rice yields were mostly below 6 Mg ha^{-1}.

Xuan et al. (1997) carried out 34 NPK fertilizer experiments in 11 provinces located in 15 agro-ecological zones of the MD and covering 17 soil types. Rice was directly sown at 200 kg ha^{-1} at all sites. Fertilizer K applications were 0, 25, 50, 90 and 100 kg K ha^{-1}, fertilizer N applications were 0, 40, 80, 120, 160 kg N ha^{-1}, and fertilizer P applications were 0, 13, 26 and 39 kg P ha^{-1}. Results showed that rice yield was generally below 5 Mg ha^{-1} in the wet season crop and mostly below 6 Mg ha^{-1} in dry season crop. At a few sites, rice yields reached 7 - 7.5 Mg ha^{-1}. Rice showed no statistically significant response to potassium application at all sites on potential acid sulfate soils, alluvial saline intruded soils, and alluvial soils. However, there was one site where rice showed response to a K application of 30 kg ha^{-1} although the amount of exchangeable K in soil was 3.6 mmol kg^{-1}, which is above the critical level of 2.1 mmol kg^{-1} (Xuan et al., 1997). Guong and Revel (2001) explained that the low yield in the 0 K treatment at this site was due to the low K/Na ratio (K/Na = 0.1) and the high Na/CEC ratio (Na/CEC = 14.2).

Guong et al. (unpublished data) found that plant K was below 15 g kg $^{-1}$ at almost all sites and was below 10 g kg^{-1} at many sites, although rice yield did not respond to K fertilizer application at these sites (Table 1.3). Response to K fertilizer application was observed only on sandy alluvial soils. Nevertheless, it was recommended that K should be applied at 30 kg K ha^{-1} to maintain adequate levels of soil K. Rice yield did also not respond to P fertilizer application in these studies. The N dose was 80-100 kg N ha^{-1} in this study, which may have not been sufficient to fully exploit the yield potential in the dry season.

Table 1.3: NPK fertilizer application (kg ha^{-1} per crop), rice grain yield (Mg ha^{-1}) and K mass fraction in grain and straw (g kg^{-1}) at some sites in the MD. (DS: dry season; WS: wet season). (Source : Guong et al., unpublished data).

Site	Crop season	Treatment (N-P-K)[a/]	Yield	K in grain	K in straw
Thoai Son-AG	DS 95-96	120-26-25	4.37	4.10	9.90
Thoai Son-AG	DS 95-96	120-39-0	4.39	4.15	9.60
Cang Long-TV	DS 95-96	120-26-25	3.98	4.79	4.29
Cang Long-TV	DS 95-96	120-39-0	2.19	5.77	4.88
Chau Thanh-TG	DS 95-96	120-26-25	6.55	4.26	8.60
Chau Thanh-TG	DS 95-96	120-39-0	6.27	4.18	8.00
Chau Thanh-AG	DS 95-96	120-26-25	6.88	3.50	9.10
Chau Thanh-AG	DS 95-96	120-39-0	6.62	2.40	7.70
Dong Cat-DT	DS 95-96	120-26-25	7.02	3.04	7.10
Dong Cat-DT	DS 95-96	120-39-0	7.22	5.60	10.10
Thanh Binh-DT	DS 96-97	120-26-50	6.46	1.60	15.31
Thanh Binh-DT	DS 96-97	120-26-0	6.06	2.44	15.52
Tam Binh-VL	WS 96	120-26-25	4.32	2.00	11.98
Tam Binh-VL	WS 96	120-39-0	4.01	2.07	11.60
Cai Lay-TG	WS 96	120-26-25	4.15	2.08	11.78
Cai Lay-TG	WS 96	120-39-0	4.01	1.70	10.67
Ke Sach-ST	WS 96	120-26-50	4.65	1.58	12.34
Ke Sach-ST	WS 96	120-26-0	4.41	1.87	13.86

[a/] Amount of NPK fertilizer application (kg ha^{-1} per crop).

1.3.3.2. Field trials conducted by Cuu Long Rice Research Institute (CLRRI)

A long-term NPK experiment on rice was established on an alluvial soil at CLRRI in Omon in 1994, with applications of 0-80-100 kg N ha^{-1}, 0-25 kg P ha^{-1}, and 0-75 kg K ha^{-1}. Until 2001, 14 rice crops had been harvested and no significant yield response to K application has been observed yet, at yield levels of about 5.5 to 6.5 Mg ha^{-1} in the dry season and 3 to 3.5 Mg ha^{-1} in the wet season. Similar observations were made in another long-term experiment conducted since 1988 at O Mon, in which fertilizer rates and yields were somewhat lower than at CLRRI (Tan et al., 1995; Dobermann et al., 1996c).

Recent data from on-farm trials conducted by CLRRI showed that site-specific nutrient management increased dry season yields of rice by about 10%. Better timing of N applications and increased K rates were the key components in this approach, resulting in increased N and K uptake as well as in greater fertiliser-N use efficiency (Tan et al., 2003).

In a recent study of Nga (2001), rice yield did not respond to K application in the dry or in the wet season, irrespective of whether the field was inside the polder without sedimentation or outside the polder with sedimentation (Table 1.4). However, yields in her study were only 4 to 5.5 Mg ha and the amount of K applied was small.

Some observations also suggested that application of K increases resistance to diseases and insect pests, particularly fungal diseases, such as brown leaf spot caused by *Cercospora oryzae* and *Helminthosporium* spp., and blast caused by *Pyricualaria oryzae* (Huber and Arny, 1985). This may be important in the MD. Mew (1991) reported that

Table 1.4: Rice yield (Mg ha^{-1}) in the dry season and wet season inside the polder without sedimentation and outside the polder with sedimentation. (Source: Nga, 2001).

Treatment[a/]	Inside polder		Outside polder	
(N-P-K)	Dry	Wet	Dry	Wet
0-0-0	4.43 b[b/]	3.46 b	6.02 ab	3.73 b
0-26-25	4.22 b	3.70 b	6.29 a	4.31 ab
100-0-25	5.58 a	4.01 ab	6.09 ab	3.61 b
100-26-0	5.37 a	4.40 a	5.69 ab	4.61 ab
100-26-25	5.54 a	3.92 ab	5.33 b	3.91 ab
50-26-25	5.63 a	4.34 a	6.50 a	4.79 a

[a/] Numbers refer to rates of N, P and K in kg ha^{-1} applied in each treatment.

[b/] Data followed by the same letter in the same column are not significantly different at 5% level.

sheath blight (*Rhizoctonia solani*) infection levels are typically high in rice crops with dense canopies that receive high N rates. On-farm studies in the Red River Delta of northern Vietnam indicate that severe sheath blight infection can cause 25-50 % yield loss in rice crops with poor canopy development and deficient foliar N concentration. In these fields, the K in flag leaves sampled at flowering was less than 10 g kg^{-1} at most of the farm sites, with values as low as 7 g kg^{-1}, suggesting severe deficiency (Trung et al., 1995). Whether the unusual severity of sheath blight in N deficient canopies is related to plant K deficiency remains unknown.

In conclusion:

- Yield response to K application is rare at present yield levels of 4 to 6 Mg ha^{-1}.
- Low K mass fraction in rice straw is an indicator of low K supply by soils.
- Because no good measurements on components of the K budget of whole cropping systems have been made, nor on the dynamics of K release from the soil under field conditions, it is still a question whether the indigenous supply of K from soil, and the inputs by irrigation and sedimentation are really high enough to sustain present and future K requirements of rice.
- Some observations suggest that application of K increases resistance to diseases and insect pests, which may also be important in the MD, particularly with regards to fungal diseases.

1.4. Potassium status in soil and sediments of the Mekong Delta.

1.4.1. Potassium status in soils

The major part of the rice growing areas in the Mekong Delta is on alluvial soils which are geologically young and mineralogically rich in mica (24-50 %), as reported by

Uehara (1974). Mineralogical analysis of the clay fractions in 43 soil samples from all over the Mekong Delta showed that on average one half of clay minerals is illite, one third is kaolinite and one sixth is smectite (Brinkman et al., 1985). Guong et al. (2001) also found in almost all other alluvial soils, illite content was 40-45 % and smectite was only 10-15 % (Table 1.5), but in the Cai Lay area, where triple cropping has started about 30 years ago, illite content was only 20 % and smectite content was 40%. The transformation of illite to vermiculite and to smectite under cropping condition may be the reason for the low illite content in Cai Lay soils.

Because of the lack response of rice yield to K application on alluvial soils, the interest of soil fertility researchers in the Mekong Delta was directed to other nutrients. As a result, in almost all fertilizer experiments, total N and available P were analyzed, but exchangeable K rarely. Soil K fractions have not been studied in detail. Studies on the reliability of methods for the determination of crop response to K application have started in 1995 (Nga and Cassman, 1994). A very low correlation was found between various exchangeable K extraction methods and rice yield in the field. A limitation of this study was that it was only tried to relate exchangeable K to rice yield, and not to K uptake by rice.

In a greenhouse study, Hoa et al. (1998) examined the correlation between rice growth and exchangeable soil K and boiling 1 M HNO_3 extractable K for 10 soils, representing 4 major soil groups in the Mekong Delta. Their conclusion was that exchangeable K extracted by 1 M NH_4OAc at pH 7 showed a good correlation with K uptake and was a reliable index for K supply in soils in the Mekong Delta. Non-exchangeable K extracted by 1 M boiling HNO_3 was also correlated with total K uptake, but net non-exchangeable K (difference in extracted K between 1 M HNO_3 and 1 M NH_4OAc) showed no correlation with total K uptake.

In about 75% of 24 farms sampled in Can Tho province, extractable soil K was above 2.2 mmol kg^{-1} (Tan et al., 2003). They also suggested that depletion of soil K may occur, depending mainly on the cropping intensity. For example, average resin-extractable K in 32 farms of Cantho province was only 48% of that measured in a +NPK

Table 1.5: Mineral composition of surface soils (0-20 cm) of rice soils in the Mekong Delta (Source: Guong, 2000).

Soil	Site	Quartz	Kaolinite	Illite	Smectite	Vermiculite	Chlorite	Interstratied Smectite-Chlorite
Typic Ustifluvent, fulvic	Phu Tan	15	10	45	15	-	15	-
	Thoai Son	20	10	40	15	-	15	-
	Tan Hiep	20	10	40	-	10	20	-
	Phung Hiep	10	5	50	-	10	25	-
Typic Eutropepts	Long Ho	5	15	40	-	25	15	-
Typic Eutropepts Umbric, aquic	Cai Lay	-	15	20	40	-	10	15
	Thanh Binh	10	10	40	20	-	20	-
	Chau Thanh TG	15	15	40	20	-	10	-
	Ke Sach	15	10	45	15	-	15	-
Typic Tropaquepts Salic	Cau Ngang	10	10	50	15	-	15	-
Typic Ustropepts Salic	Vinh Loi	10	10	45	10	-	25	-
	Cau Ke	15	10	45	10	-	20	-
Typic Hydraquentic Sulfaquepts	Thanh Hoa	15	20	30	-	-	35	-
Sulfic Tropaquepts Sulfuric	Dong Cat	15	10	45	15	-	15	-
	Chau Thanh AG	10	10	45	-	10	25	-
Sulfic Tropaquepts Sulfuric fulvic	Hon Dat	20	10	40	-	-	30	-
Sulfic Tropaquepts Sulfuric rhodic	Cang Long	10	10	45	15	-	15	-
Hydraquents sulfic, Sulfuric profond	Tam Binh	5	15	50	-	-	30	-
Sulfic Tropaquepts Sulfidic salic	Binh Dai	20	20	40	10	-	10	-
Sediment of Mekong river	Can Tho	15	10	50	-	-	10	-

(balanced nutrition) treatment of the new long-term experiment at CLRRI in Omon (Dobermann et al., 1996a). Compared to other sites in Asia, soil from the same experiment had relatively high initial K release to an ion exchange resin capsule, but little further release during a 2-wk anaerobic incubation period (Dobermann et al., 1996b). In a situation of high crop K demand, this may cause K deficiency.

Hoa et al. (1998) also analyzed some other K fractions in soil. K extracted by boiling 1 M HNO_3 ranged from 6.4 to 10.2 mmol kg^{-1} in recent alluvial soils. Exchangeable K extracted with 1 M NH_4OAc at pH 7 (Page et al., 1982) fell within the medium-low to medium range from 2.7 to 4.5 mmol kg^{-1} in recent alluvial soils. Although this range was higher than the commonly used critical level of 2 mmol K kg^{-1} (Jones, 1982; Dobermann and Fairhurst, 2000), it was concluded that exchangeable K in recent alluvial soils was marginal to adequate (Hoa et al. 1998).

In the greenhouse experiment conducted by Hoa et al. (1998), it was also shown that intensive cropping would result in a decrease of exchangeable K and subsequently to a decrease in plant growth due to K deficiency. Under field conditions, K uptake is not as intensive as in a greenhouse exhaustion experiment, and rice grown under field condition may not yet respond to K application, as shown by Ren and Hoa (1993).

1.4.2. Potassium status in sediments

Studying nutrient contents in sediments and soils of the Mekong Delta, Uehara et al. (1974) reported small but significant differences between sediments and soils in mineral and acid extractable nutrient contents. The sediment samples were higher in mica, hematite, kaolinite, feldspar, and chlorite-montmorillonite and lower in aluminum contents than the soil samples. Sediments were richer in 0.3 M HCl- extractable P, K, and Ca than soils. They calculated that (0.3 M HCl extractable) 1 kg P, 3.2 kg K, 4 kg Mg, and 50 kg Ca per hectare are applied by the deposition of one millimeter of sediment with a bulk density of one g cm^{-3}. They concluded that even if these computed values were double, the sediment deposit could not significantly increase the fertility of the delta soils. Moreover, farmers tend to build small dams (bunds) around the fields to protect the rice in the wet season, and this may prevent up to 60% of the sediment input to the field via flooding (Center of Research and Development of the Mekong Delta, 1998). Nevertheless, it was often believed that the regular supply of nutrients and sediments by the Mekong water would replenish K removed by rice. Only few attempts have been made to quantify sediment amounts and the availability of K from sediments. Nutrients input from the sediment may be the reason why in the study of Nga (2001) rice yields outside the polder were on average 0.5 Mg ha^{-1} higher than those inside the polder in the dry season after flooding (Table 1.4). Another reason for higher yield in the fields outside the polder may have been that the triple cropping system inside the polder does take up more nutrients than the double cropping system outside the polder. Available K in the sediment, extracted by 0.3 M HCl, was 4.8 mmol kg^{-1} in her study.

1.5. Potassium balance in the Mekong Delta and other Asian regions

1.5.1. Estimates of K balance in the Mekong Delta

Estimating the complete K balance in an irrigated rice field would require measurement of K outputs due to crop removal, leaching, runoff, and seepage and of K inputs from fertilizer, irrigation water, rainfall, seepage and sedimentation. Many of these components are site-specific and have not been measured and included in balance calculations in the past.

Rain water is reported to be low in K and only occasionally annual inputs may exceed 10 kg ha^{-1} (Abedin Mian et al., 1991; Handa, 1988). Assuming an annual rainfall of 1000-2000 mm, most sites of irrigated rice cultivation in Asia probably have annual inputs from rainwater in the range of 3 to 10 kg K ha^{-1} (Dobermann et al., 1998).

Concentrations in river or canal water range from 1 to 5 mg K l^{-1} (Kawaguchi and Kyuma, 1977; Handa, 1988). Abedin Mian et al. (1991) reported a value of 2.4 mg l^{-1} for K in irrigation water in Bangladesh. Using an estimated net irrigation water supply of

700-1200 mm, the K input per rice crop would be in the range of 7 to 60 kg ha^{-1} if surface water is used (Dobermann et al., 1998).

In rice fields, soluble nutrients can be lost through surface drainage, lateral seepage and percolation. In a rice growing area, surface drainage from one field is often an input for a neighboring field. Similarly, the lateral movement of subsurface water is mostly offset by incoming seepage from some other fields. It is, therefore, generally assumed that net nutrient losses due to surface drainage and seepage are small, except in peripheral fields with considerable difference in elevation between fields (Tuong et al. 1994).

Water percolation in rice fields has been reported to vary from 0.1 to 10 mm d^{-1} and is influenced by a variety of environmental and soil-related factors (Table 1.6). Usually, runoff due to overflow over bunds does not often happen, and therefore, is of minor importance. In many cases, inputs from rainfall and irrigation have been assumed to be comparable or even smaller than nutrient losses due to leaching, Therefore, inputs via rainfall and irrigation are suggested to represent not a net gain in nutrients (Abedin Mian et al., 1991; Haque 1995, Dobermann et al., 1998). However, these assumptions have not been verified yet in different environments.

In the Mekong Delta, little information is available on the various K inputs and outputs. The amounts of K remaining in the field from rice straw or rice stubble are different depending on crop residue management, length of rice stubble and K content in the crop residues. After the dry season crop, rice straw mainly remains in the field and is then burnt. In wet season crops, however, the field is often wet or flooded so that all plant material is removed out of the field for off-side threshing. Straw is often used for mushroom cultivation or for other purposes, but the remaining stubble is left the field. In areas where three crops are grown farmers will start the next crop 7-10 days after harvesting the previous crop. Therefore, rice stubble must be short because it is difficult to do land preparation and seeding if there is a large amount of residue in the field.

Drainage after land preparation and puddling can be a significant K output. Drainage water is often very turbid if farmers remove it right after puddling; but it

Table 1.6: Water percolation rate (mm d^{-1}) in rice field; a compilation of literature results.

Percolation rate mm day^{-1}	Remarks	Source
0.1 – 10[a/]		Greenland (1985), Hardijoamidjojo (1992), Shamar & De Datta (1992), Humphreys et al. (1992)
negligible	in alluvial soils of Punjab having 2:1 clay minerals	Sekhon (1976)
2.6 – 3.6	well- puddled soil	Tuong et al. (1994)
0.0, 0.0, 10.0	at 0.0, 1.0 and 2.0 m from drain pipe	Adachi (1990)
2.8	average value of 198 soils	Jo and Um (1990)

[a/] In sandy soils much higher rates were found.

contains little sediment if some time is allowed for sediment to settle down before drainage. Whether this loss is important is unknown.

For 24 on-farm sites in O Mon over the period 1997 to 2000, calculated K balances of rice fields revealed that the K balance depended mainly on K fertilizer application, grain yield and straw management (A. Dobermann, unpublished data). On farms where fertilizer K application was below 50 kg ha^{-1}, the K balance per rice crop grown was negative from -2 to - 64 kg ha^{-1}, with an average of –29 kg ha^{-1}. On farms where K fertilization was 50-70 kg ha^{-1}, K balance was positive (0.4 to 27 kg ha^{-1}). These calculations were based on the assumptions that 60% of K in straw remained in the field through K in the ash after burning rice stubble, and that K input from rain and irrigation water was equal to K loss by leaching.

1.5.2. Potassium balance in Southeast Asia

Doberman et al. (1996c) used a simplified approach for calculating the partial net K balance in long-term experiments in Asia, using data on fertilizer input, above ground uptake, and recycling of K with straw. The average partial net K balance was highly negative in all NPK combinations tested (-34 to – 63 kg ha^{-1} per crop cycle). Fertilizer K application at an average rate of 38-44 kg ha^{-1} in the NK and NPK treatments was not sufficient to match the K removal at most sites. Extractable K in the NPK treatments was not significantly different from values in the control plots at seven sites, indicating no accumulation of soil K from application of K fertilizer at the rate used. Their conclusion was that in most intensively used rice-growing regions, K inputs do not match net K removal from the system, and that there is a continuing mining of soil K.

Dobermann and Witt (2000) computed "average" K balances for irrigated rice in Asia (Table 1.7) using data collected from a large number of on-farm studies. In their study more conservative assumptions were made than in the previous study, but the results still suggest a negative K balance of about –26 kg K ha^{-1} per crop. The assumption was made that nutrient inputs via irrigation and rainwater were roughly equal to leaching losses (Dobermann et al., 1998). Net removal with straw included nutrients lost due to removal or burning of crop residues and was estimated from plant nutrient accumulation in straw, amount of residue remaining, and the predominant crop residue management practice at each site.

Table 1.7. Estimated average input-output balance of K (kg ha^{-1}) in intensive rice systems of South and Southeast Asia with an average yield of 5.2 Mg ha^{-1}. (Dobermann et Witt, 2000).

Inputs and outputs	K (kg ha^{-1})
In1: Fertilizer	17
In2: Farmyard manure	05
Out2: Net removal with grain	13
Out3: Net removal with straw	35
Input-output balance	-26

It is necessary to say that the estimated K balances are associated with large uncertainties about K inputs from water and sediments and also about K output via leaching. Therefore detailed measurements of K inputs via rain, irrigation water and sediments, and K output via leaching and removal of straw are required to be able to establish accurate K balances.

1.6. Structuring the problem and problem solving

Rice cultivation is becoming more and more intensive in the Mekong Delta. Growing three rice crops in a year shortens the time for the replenishment of available K from non-available K pools. Moreover, K input via sediment is decreasing, as farmers tend to prevent flooding of the land to be able to increase the number of crops per year. Further, due to high fertilizer N and P applications, the removal of K in grain and straw has increased. Hence, it is likely that soil K is depleted steadily (Fig 1.2).

Although rice soils in the MD have shown little response of rice yield to K fertiliser application in many long-term fertiliser experiments, K in rice straw at harvest is lower than or at the critical value of 10 g kg^{-1}. Exchangeable K on alluvial soils is just above the critical level, and is rated as medium-low to medium. One may conclude that K fertilisation is not very essential for rice in alluvial rice soils and that small amounts of K fertiliser are sufficient and safe for soil K maintenance. However, such a recommendation is weak if it is not based on sufficient information about soil K budgets and on an understanding of soil K behaviour under cropping conditions. The report of Luat (2001) on the inconsistency of K fertiliser recommendations for rice in the Mekong Delta clearly showed the lack of a scientific basis for these recommendations.

The K deficiency problem in rice growing that farmers in China and India are now facing can be the future problem for farmers in the Mekong Delta if soil K is not well maintained. The increased incidence of nutrient imbalance-disease interaction in general with intensified rice cropping should also be considered. Scientific information is

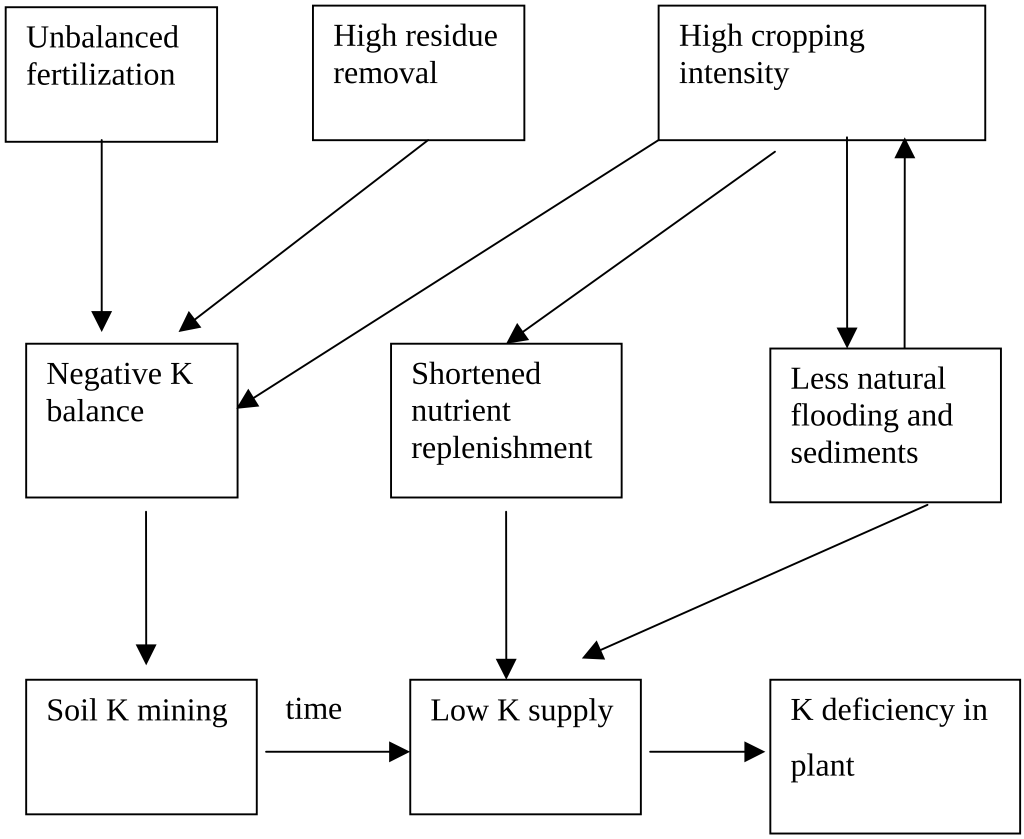

Figure 1.2: The hypothetical cause-effect relationship in K deficiency in wet land rice.

therefore required to predict the long-term supply of K in alluvial rice soils in the Mekong Delta before K deficiency appears.

The *main objectives* of the research described in this thesis are to increase the understanding of K dynamics in the wetland rice cropping systems, and to provide sound guidelines for adequate K management in these systems in the Mekong Delta. To be able to achieve these objectives, results of field, greenhouse and laboratory experiments were combined and analysed using budget calculations and simple models.

To get a complete assessment of K budgets, all K inputs and K outputs need to be measured. So far, K balances have mainly been calculated based on a partial consideration of input and outputs. Whether measurements of all K inputs and all K outputs are essential for assessing the K balance accurately, especially for the Mekong Delta, needs to be clarified. This question will be addressed in Chapter 2.

To be able to predict soil K supply and changes in soil K pools over time, the chemical extraction methods for assessing the size of different soil K pools need to be tested first, and this will be addressed in Chapter 3. Secondly, the kinetics of K adsorption-desorption, and fixation-release processes, and reaction rate constants need to be determined, and this will be discussed in Chapter 4.

Chemical extraction methods for K such as 0.01 M $CaCl_2$, 1 M NH_4OAc pH 7, 1 M HNO_3 and 0.2 M NaTPB have been studied intensively in the past (McLean, 1976; Houba et al., 1986; Portela, 1993; Eckert and Watson, 1996; Cassman et al., 1990; Dobermann et al. 1996b; Nair et al., 1997; Van Erp, 2002; Cox et al., 1999). However, less certain is whether these extraction methods are suited for characterizing different K pools as used in simulation models of K dynamics. Reports on the kinetics of K adsorption-desorption and fixation-release processes do present rate coefficients of K transfers among pools, but these rates have rarely been compared to the rate of transfer under cropping conditions and also have rarely been used for a predictive understanding of the short- and long-term soil K supply. Model development is elaborated in Chapter 6 to increase the understanding of the behavior of K in soil in response to plant uptake under fertilization and no fertilization conditions.

Adequate K management of rice soils must consider soil K availability and K fertilization in relation to the specific geography, flood characteristics, soil K status, and required rice yield levels. It is hypothesised that the assessments of complete K budgets and soil K dynamics can be brought together in a simulation model, to enable the prediction of future needs for K fertiliser (Chapter 7). Once such a model is in running order, it can be used to estimate the indigenous supply of K from soil, and for a quantitative evaluation of the fertility of soils under different environmental conditions (e.g. Janssen et al., 1990; Witt et al., 1999). Such a model may then form the starting point for the development of a practical decision guide on K management, to be used by extension services and farmers.

Profile description in harvested rice field at Cau Ke.

CHAPTER 2

ASSESSMENT OF POTASSIUM BUDGETS IN DOUBLE AND TRIPLE RICE CROPPING SYSTEMS IN THE MEKONG DELTA

2.1 Introduction

Nutrient balances are important for evaluating the sustainability of cropping systems and for improving nutrient management. Many studies in rice cropping systems in Asia indicate that K balances are negative, mostly in the range of –20 to –50 kg K ha^{-1} per crop (Patnaik, 1978; Bajwa; 1993, Dobermann, 1996c). Dobermann and Witt (2000) estimated an average K balance of –26 kg K ha^{-1} per crop, using data from 207 rice farms in Asia. So far, most of these studies on K input-output balances for wetland rice in Asia were simply based on the amounts of fertilizer applied as input and the amount of K removed by the crop as output (e.g. Nambiar and Ghosh, 1987). Some studies included assumptions on K in irrigation water (e.g. Bajwa, 1993) or on rice straw management (e.g. Patnaik, 1978) using simplified budgets. Others calculated the *partial* K balance from fertilizer input, aboveground uptake and crop residue remaining in the field (e.g. Dobermann et al., 1996c). Inputs of K from rainfall and irrigation water were often assumed to be comparable or smaller than nutrient losses due to leaching and thus do not represent a net input of nutrients (De Datta et al., 1988; Abedin Mian et al., 1991, Haque, 1995; Dobermann et al., 1998), but these assumptions have not been verified yet.

A *complete* K budgeting approach includes all inputs via chemical fertilizer, rain and irrigation water, sediment in irrigation water and flood water, and all outputs via harvested product, residue removal, leaching, erosion, and water runoff. Comparisons of *partial* K balances with *complete* K balances may reveal which input and output entries are important and which are not.

According to Janssen (1999), a differentiation between available and non-available nutrients is useful in nutrient balance studies. Such a differentiation has not yet been made for K in rice cropping systems. This is important as not all inputs of K via sediment can be considered as available K. Calculation of balances of available and non-available K was expected to be helpful in identifying the severity of K depletion. Attempts have been made by Nga (2001) to measure the amount of sediment in floodwater and to analyze available K as a measurement of sediment quality. However, complete K budgets of both available and non-available K have not been established yet.

The objectives of this study are (i) to quantify K budgets in double and triple crop systems with different rates of sedimentation, straw management and K fertilization, (ii) to examine whether a *complete* budget rather than a *partial* budget was required for assessing the supply of K to rice in the Mekong Delta, and (iii) to evaluate the importance of differentiation between balances of available and non-available K for K management.

2.2. Nutrient budgeting

2.2.1. General concepts

A nutrient budget is meant to be an ‘account’ of nutrient flows to (inputs) and out (outputs) of a certain, clearly defined, agroecosystem (e.g. field, farm). Nutrient balance is the difference between the sums of nutrient inputs and nutrient outputs. A positive balance, sometimes designated as nutrient surplus or excess, points to enrichment, and a negative balance, sometimes designated as ‘deficit’, to depletion of the system considered (Janssen, 1999).

Nutrient budgets may relate to different spatial and temporal scales. Spatial scales may include continents, countries, districts, watersheds, farms, or individual fields

Usually, the appropriate time steps are longer the larger the spatial dimensions of the system. Many studies on nutrient budgets were conducted in small experimental plots or refer to fields with sizes ranging from about 0.1 to tens of hectares. The corresponding time step is one year or one growing season in cases where there are two or more crops per year. At each scale, nutrient flows may be classified into inputs, outputs and internal flows (Janssen, 1992; Smaling et al., 1996; Janssen, 1999).

In this study, the K budget is quantified for a soil-plant system at the field scale. For rice cropping systems in the Mekong Delta, the most relevant inputs (INs) and outputs (OUTs) for K are listed in Table 2.1.

Janssen (1999) split each nutrient flow into two components: available nutrients and nutrients that are not available within the time step considered. The nutrients that are not immediately available are denoted as "NIA nutrients". The nutrient budget was differentiated into two budgets. The balances of these budgets were indicated by BALAV for available nutrients and BALNIA for NIA nutrients.

Table 2.1: Inputs and outputs of K for rice cropping systems in the Mekong Delta, as considered in this study

Code	Description
Inputs	
IN 1	Chemical fertilizer
IN 2	Rain water
IN 3	Irrigation water
IN 4	Sedimentation via annual floods
Outputs	
OUT 1	Harvested products
OUT 2	Removed crop residues
OUT 3	Leaching
OUT 4	Erosion
OUT 5	Run off water

$$BALAV = \sum f_{ai}\, IN_i - \sum f_{ai}\, OUT_i$$

$$BALNIA = \sum (1-f_{ai})\, IN_i - \sum(1- f_{ai})\, OUT_i$$

where f_{ai} was the fraction of available nutrients and $(1-f_{ai})$ is the fraction of nutrients that are not available within the time step considered.

The sum of the two represents the total input-output budget:

$$BALNUT = \sum IN_i - \sum OUT_i$$

2.2.2. K budgets in the present study

The split of nutrient balances into available and not immediately available nutrients is helpful in identifying the problem and appropriate actions. Both negative and positive balances for available and not immediately available nutrients may require a management response.

We made a distinction between K present in the soil solution (denoted by 'soluble K') and K present in or attached to solid soil particles. Chemical fertilizers, rain water and irrigation water was assumed to be all soluble K. Also K in the OUTs 1, 2, 3 and 5 was considered as 'soluble', because K has to enter the soil solution before it can be taken up by crops or be lost by leaching or runoff. K present in solid particles (in sediments of IN 4 and OUT 4) was split according to the three extraction methods used in this study: (i) K(NH_4OAc) extracted by 1 M NH_4OAc at pH 7 and at a soil:water ratio of 1:20 at one hour shaking time, (ii) K(NaTPB) extracted by 0.2 M sodium tetraphenyl borate (NaTPB) during 5 min incubation (Cox et al;1999), and (iii) total K determined by a mixture of concentrated HF and $HClO_4$ (details of the chemical analysis are given in the Annex 2.1). This resulted in four K balances:

BAL(soluble K) = (IN1 +IN2 + IN3) – (OUT 1 + OUT 2 + OUT 3 + OUT 5)

BAL(KNH_4OAc) = BAL(soluble K) + IN 4 (KNH_4OAc) – OUT 4 (KNH_4OAc)

BAL(KNaTPB) = BAL(soluble K) + IN 4 (K(NaTPB) – OUT 4 (KNaTPB)

BAL (total K) = BAL(soluble K) + IN 4 (total K) – OUT 4 (total K)

2.3. Materials and Methods

2.3.1. Experimental fields

Representative double and triple rice crop areas which differed in cropping intensity, rates of fertilizer K application and of sedimentation, and in crop residue management in the Mekong Delta were selected for the study (Table 2.2). Information on cropping systems, cultural practices, flooding characteristics in rice growing areas in the Mekong Delta have been presented in Chapter 1.

The NP and NPK plots of a long-term fertilizer experiment at the *Cuu Long Rice Research Institute (CLRRI)* in Omon district, Can Tho province, established in 1994 were used in this study as representative sites for the double crop rice system with relatively

Table 2.2: Cropping systems considered in the K balance studies.

Code/location	Cropping intensity	Sedimentation	Residue management	K fertilizer application
CLRRI- NP	double	little	removal	none
CLRRI-NPK	double	little	removal	high
An Phong	double	much	incorporation after dry season crop, partially removed in other crops	moderate
Thoi Thanh	triple	much	incorporation after dry season crop, partially removed in other crops	low

little annual sediment deposition. In the NPK plots, a total of 75 kg K ha^{-1} was applied to each rice crop in two portions: one half at 7-10 days after sowing (DAS) and the other half at 42-45 DAS. Twelve crops have been grown until the sampling period (March 2000).

A field in *An Phong-Dong Thap* province, belonging to the Rice Variety Screening Center of Dong Thap province was chosen as a representative example for double rice crop system with much sediment deposition. K fertilizer was applied at 20 days after sowing (DAS) (6.6 kg ha^{-1}) and at 30 DAS (28.5 kg ha^{-1}). An exception occurred in 2001, when a ratoon rice crop was tried out by the farmer in the late wet crop season without any fertilizer application.

A farmer's field in Thoi Thanh- O Mon district of Can Tho province was selected as an area representing a triple crop system with much sediment deposition. This site was about 200 m from the O Mon riveret (a branch of Hau Giang river) (see Chapter 1 for the location and name of two branches of the Mekong River), and receives much sediment in comparison to CLRRI, which was 5 km away from the O Mon Riveret**.** Data were collected during three consecutive seasons; dry season 2000-2001, early wet season 2001 and late wet season 2001. Ultra-short duration rice varieties (90-95 days) were grown. K fertilizers were applied at rates of 6.6 kg ha^{-1} at 20 DAS and 6.6 kg ha^{-1} at 30 DAS.

2.3.2. Methods for assessing K inputs and outputs

2.3.2.1. K inputs

The input by *chemical fertilizer (IN1*) is the amount of fertilizer K applied per hectare to each crop.

Rainwater samples (IN2) were collected in duplicate during the rainy season in Can Tho in years 2000 and 2001, and in An Phong-Dong Thap in 2001. The amount of rainfall was obtained from weather stations at Can Tho and in Dong Thap province. Soluble K was measured by atomic absorption spectrophotometer (AAS).

Irrigation water samples (IN3) from the irrigation canal connected directly to the fields were collected at each site in duplicate in the dry season of 2000, and the dry and wet seasons of 2001. Water samples were taken twice in every crop and each sample was 5 liters. Water samples were first filtrated and K in irrigation water was measured by AAS. The quantity of irrigation water brought into the experimental area was derived from the change in water level before and after each irrigation event measured with a measuring rod. All measurements were taken before the soil dried out. These measurements were done only at CLRRI in NP and NPK plots; estimates for the other sites were derived from the results obtained at CLRRI.

K inputs via *sediment in irrigation and f loodwater (IN4)* as suspended sediment were measured in irrigation water samples, and sedimentation during the flood period from mid July to December was determined using sediment traps. The sediment traps were not used during the rice-growing period from December to July because possible redistribution of sediment within the plots would make an assessment of net input impossible. A sediment trap made of a flat wooden board, 0.4 m x 0.4 m in size and 5mm thick, was placed tightly at a corner of the experimental sites. The surface of the wooden sheet was aligned with the surface of the soil. The sediment traps were placed in the four replicates of the control treatments at CLRRI and in five replicates in the fields at Thoi Thanh and An Phong. The traps were collected after the flood had receded in 2000 and 2001. At each sampling time at the end of the flood season, the thickness of the sediment layer was measured. Sediment samples per unit of area (280 cm^2) in the middle of the traps were collected, dried at 40^oC, weighed for determining sediment yield and used for chemical analysis. Sediment yield at 40^oC of 280 cm^2 was converted into Mg ha^{-1}. The sediment samples were analyzed for total dry weight, total K, 1 M ammonium acetate extractable K, 0.2 M NaTPB extractable K, particle size density (determined by picnometer), pH_{H2O} (1:1), total N, available P by 0.05 M H_2SO_4, CEC and exchangeable Ca, Mg and Na in 0.01 M unbuffered $BaCl_2$.

2.3.2.2. K outputs

Rice grain, straw and stubble yields (OUTs 1&2) were determined and K in grain, straw and stubble was analyzed to calculate the quantities of K in grain, straw and stubble that were removed from or remained in the field. Stubble was defined as the part of rice plant left after cutting during harvest. Measurements of rice stubble were done only at An Phong and Thoi Thanh. Stubble K content at IRRI was estimated from the ratio of stubble K to total K uptake found at Thoi Thanh. Total K in rice grain, straw and stubble was determined by AAS after digestion of the samples in H_2O_2 and concentrated H_2SO_4.

K leaching (OUT 3) was assessed by determination of K in soil solution and in situ measurements of the vertical percolation under flooded conditions. Soil solution samples were collected from two depths (7 cm below soil surface and within the hardpan) at 3 days and at 20-25 days after K application. The procedure for taking soil solution samples was similar to the one described by Vamadevan and Samy (1979). A plastic tube of 2 cm diameter and 100 cm long with 5 cm long holes (holes were encased with fine cloth to prevent clogging) at 20 cm from the tip was pushed into the soil until the collection zone was reached. The space between soil and the tube was filled with clay, compressing it firmly to avoid preferential flows of irrigation water along the tube. The tube was closed to avoid entering of rainwater. Water that had come in the tube during installation was sucked out using a syringe. After that, new incoming water was collected at each sampling time. Soil solution samples were filtered and analyzed for soluble K by AAS.

Percolation was measured during the same three consecutive days on which the soil solution was sampled. A single ring infiltration cylinder of 30 cm diameter was pushed into the soil up to the hardpan, and covered to prevent evaporation. The percolation rate (mm day^{-1}) was inferred from the daily change in water level inside the ring. At CLRRI, measurements were done in all four replicates of the NPK plots, with five records per replicate. Also in Thoi Thanh and An Phong 5 records were made. Reading error was 0.5 mm.

Sediment (*OUT 4*) can be lost via drainage water after puddling the field. If farmers removed drainage water right after pudding, the water was often very turbid but it contained little sediment if it was drained on the next day for sowing rice. Water drainage samples in Thoi Thanh were analyzed to calculate the amount of sediment loss by drainage.

Sometimes, top soil was removed from the land by farmers to facilitate gravity irrigation. Farmers at the Thoi Thanh site routinely removed sediments to the canal at one side of the field during land preparing (after floodwater had withdrawn from the field at the end of the flood season). After 3-4 years, this canal will be filled with sediment and the farmer will restore the canal by removing the sediment to his fruit garden. In areas where no fruit garden is nearby, farmers remove sediments to bunds surrounding the fields to form an increasingly larger bund for vegetable cultivation.

In irrigated rice fields, *water runoff* (*OUT 5*) may occasionally occur from August to November (mainly in flood periods) due to heavy rains. It was not measured in this study.

2.4 Results

2.4.1. K inputs

2.4.1.1. Rain water (IN 2)

In general, the K concentration in rain water ranged from 0.3 to 3.3 mg l^{-1} (Table 2.3). It was relatively high in the beginning of the rainy season, decreased until about August when the rainfall was high, and increased again when rainfall was low at the end of the rainy season. Some interpolations and extrapolations were made for the missing data on K concentration in some months based on the parabolic curve fitting in Fig 2.1. Total K input from rain water ranged from 6 to 10 kg $year^{-1}$ at a total rainfall ranging from 1461 to 1911 mm (Table 2.3).

Table 2.3: K concentration in rain water, rainfall amount and total K input via rain water in Can Tho and Dong Thap province in year 2000 and 2001. Measured data of K concentration in Italics, others from interpolation and extrapolation (see Fig 2.1).

Can Tho								Dong Thap			
Rainy season 2000				Rainy season 2001				Rainy season 2001			
Month	Concentration mg l^{-1}	Rainfall mm	K input kg ha^{-1}	Month	Concentration mg l^{-1}	Rainfall mm	K input kg ha^{-1}	Month	Concentration mg l^{-1}	Rainfall mm	K input kg ha^{-1}
Jan	1.80	2	0.04	Jan	0.88	0	0.00	Jan	3.31	11	0.36
Feb	1.38	0	0.00	Feb	0.69	0	0.00	Feb	2.60	0	0.00
Mar	*1.03*	18	0.18	Mar	*0.54*	113	0.61	Mar	1.99	48	0.95
Apr	*0.74*	100	0.74	Apr	*0.42*	55	0.23	Apr	1.47	146	2.14
May	0.52	260	1.34	May	0.33	173	0.58	May	*1.04*	167	1.74
Jun	0.36	240	0.87	Jun	*0.28*	187	0.53	Jun	*0.71*	237	1.69
Jul	0.27	292	0.80	Jul	*0.27*	202	0.54	Jul	0.48	164	0.79
Aug	0.25	184	0.46	Aug	*0.29*	223	0.64	Aug	*0.35*	167	0.58
Sep	0.30	214	0.64	Sep	*0.34*	148	0.51	Sep	*0.31*	207	0.64
Oct	*0.41*	360	1.48	Oct	0.43	383	1.64	Oct	0.37	185	0.68
Nov	*0.59*	99	0.58	Nov	0.55	49	0.27	Nov	0.52	113	0.58
Dec	0.83	142	1.19	Dec	0.71	3	0.02	Dec	0.77	16	0.12
Total amount		1911	8	Total amount		1535	6	Total amount		1461	10

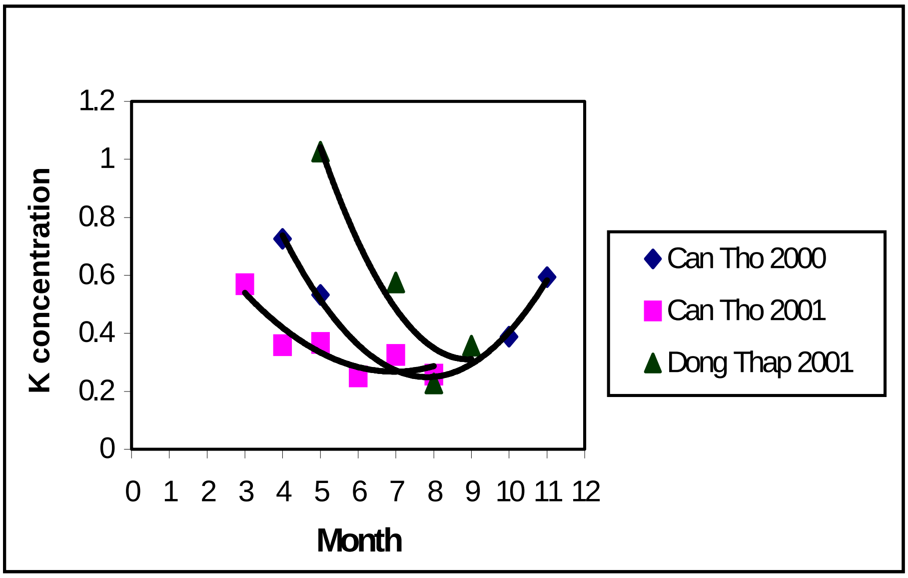

Fig 2.1: Concentrations of K in rainwater (mg l^{-1}) in Can Tho during the months of the years 2000 and 2001and in Dong Thap during 2001.

2.4.1.2. Irrigation (IN 3)

At the three experimental sites, K concentration in irrigation water ranged from 1.5 to 2.5 mg l^{-1} (Table 2.4). Amounts of irrigation water measured at CLRRI was 2300, 2400 and 3000 m^3 ha^{-1} in wet season 00, dry season 00-01 and wet season 01, respectively. In wet seasons, irrigation was often stopped when amount of rainwater was large. In the dry season of 2000, the amount of irrigation was low, because of the rains taking place in March. Total K input via irrigation water, as calculated for a relative small amount of irrigation water of 2500 m^3 ha^{-1} or 250 mm and a relative large amount of 5000 m^3 ha^{-1} or 500 mm at the 3 sites, ranged from 4 –12 kg ha^{-1} (Table 2.4).

Table 2.4: K concentration in irrigation water and ranges of calculated K input per crop by irrigation at the experimental sites.

Crop	Sampling time	K Concentration, mg l^{-1}			Range of K input from irrigation water [a/], kg ha^{-1}		
		CLRRI	An Phong	Thoi Thanh	CLRRI	An Phong	Thoi Thanh
wet 00	Jun-00	1.89	-	-	-	-	-
	Jul-00	1.49	-	-	-	-	-
	average	*1.69*	-	-	*4 -8*	*4 -7*	*4 -8*
dry 00-01	Dec-00	2.25	1.73	1.70			
	Jan-01	-	1.19	-			
	average	*2.25*	*1.46*	*1.70*	*6 -11*	*4 -7*	*4 -8*
wet 01	Jun-01	2.40	2.09	2.21	-	-	-
	Jul-01	2.45	2.05	2.15	-	-	-
	average	*2.43*	*2.07*	*2.18*	*6 -12*	*5 -10*	*5 –11*

[a/] Calculated ranges of K input for irrigation input ranges of 250 mm and 500 mm.

2.4.1.3. Sedimentation via irrigation water and annual floods (IN4)

The mass concentration of sediment in *irrigation water* ranged from 11 to 500 mg l^{-1} across the three experimental sites (Table 2.5). The sediment mass concentration depended on water source, sediment deposition process in canals, and erosion along the path. Assuming an irrigation amount of 2500 m^3 per ha per crop and an average sediment concentration value of 235 mg l^{-1} for CLRRI, deposition was 587 kg ha^{-1} of sediment per crop, or 106 g K(NH_4OAc), 366 g K(NaTPB) and 11 kg K(total) per ha per crop (NH_4OAc extractable K was 4.6 mmol kg^{-1}, NaTPB-extractable K was 16 mmol kg^{-1} and total K was 475 mmol kg^{-1} as found in flood sediment in 2001 at CLRRI).

Chemical and physical characteristics of sediments collected during the *2000 and 2001* floods are shown in Table 2.6. The sediments at An Phong and Thoi Thanh had a

Table 2.5: Concentration of sediment (mg l^{-1}) in irrigation water at experimental sites.

Site	Date	Sediment concentration
CLRRI	8 Jun. 00	501
	3 Oct. 00	231
	24 Dec. 00	147
	5 Feb. 01	149
	5 Oct. 01	146
An Phong	18 Jan 01	11
	3 Feb.01	37
	7 Jun. 01	45
	17 Jun 01	79
Thoi Thanh	4 Feb 01	182
	20 July 01	78

lighter texture than most alluvial clay soils (see Chapter 3 for soil texture of alluvial clay soils), and hence had a lower CEC.

Chemical and physical characteristics of sediments collected during the *2000 and 2001* floods are shown in Table 2.6. The sediments at An Phong and Thoi Thanh had a lighter texture than most alluvial clay soils (see Chapter 3 for soil texture of alluvial clay soils), and hence had a lower CEC.

In general, when flood water flows out of the river, the coarser fraction is deposited along the river and the finer fraction is transported further away. This resulted in silty clay soils along the river and heavy clay soils in areas far from the river. Particle size distributions of sediments in An Phong, Thoi Thanh and CLRRI reflect this pattern. An Phong located near the Tien Giang River had the highest silt and the lowest clay contents. Thoi Thanh is located farther away from the Hau Giang River and the sediments there have an intermediate texture. The CLRRI experiment station is located farthest from the river and has the lowest silt and highest clay percentage. Sediment pH values were low and in the range of those of alluvial soils in the Mekong Delta, reflecting the characteristics of parent materials from which the soils were derived. Sediment organic carbon and total N were rather high. Other chemical characteristics such as, available P, Ca, Mg, Na were low, but in the range of chemical characteristics usually observed in alluvial soils in the Mekong Delta (Chapter 3). Sediments had higher K (NH_4OAc) than soils in the same place, while K (NaTPB) and total K were comparable (Table 2.6). This probably reflects the historical decrease in available K of alluvial soils in the Mekong Delta due to cropping. The content of K (NH_4OAc) in the sediments and to a lesser degree to the content of K(NaTPB) increased with increasing distance from the river, but K total did not.

Table 2.6: Physical and chemical characteristics of sediments in flood water in 2000, and K fractions in sediments of 2000 and 2001 in CLRRI, An Phong and Thoi Thanh.

	CLRRI	An Phong	Thoi Thanh
Characteristics of sediment in flood 2000			
Sand fraction (g kg^{-1})	4	51	6
Silt fraction (g kg^{-1})	365	568	494
Clay fraction (g kg^{-1})	631	381	500
Particle density (g cm^{-3})	2.27	2.46	2.47
Bulk density (g cm^{-3})	0.34	0.41	0.39
pH (1:1)	4.6	4.63	4.66
Organic C (g kg^{-1})	35.9	22.33	26.10
0.05M H_2SO_4 extractable P (mg kg^{-1})	26.8	34.84	48.25
N total (g kg^{-1})	3.3	1.8	2.3
CEC ($mmol_c$ kg^{-1})	180.7	144.9	147.4
Ca ($mmol_c$ kg^{-1})	42.56	42.43	31.82
Mg ($mmol_c$ kg^{-1})	32.32	20.31	22.96
Na ($mmol_c$ kg^{-1})	2.85	1.97	2.31
K fractions in sediment of flood 2000			
K(NH_4OAC) (mmol kg^{-1})	4.62	2.66	3.09
K(NaTPB) (mmol kg^{-1})	11.67	10.81	10.83
K total (mmol kg^{-1})	459	526	556
K fractions in sediment of flood 2001			
K(NH_4OAC) (mmol kg^{-1})	4.63	2.31	2.74
K(NaTPB) (mmol kg^{-1})	16.00	14.25	16.79
K total (mmol kg^{-1})	475	557	538

Sedimentation was higher in 2000 than in 2001 (Table 2.7) because of high flood levels in 2000. The distribution of sediment depends on the local topography and the distance to the river. Wet sediment thickness was 16 mm at CLRRI, 22 mm at An Phong, and 30 mm at Thoi Thanh, showing that An Phong and Thoi Thanh were located near to the river, and CLRRI not. Depending on the amount of sediment, K inputs from K(NH_4OAc), K(NaTPB), K total were calculated (Table 2.7). Input of K(NH_4OAc) was relatively small, but input of K(total) was relatively large, ranging from 320 to 3826 kg per ha per flood.

2.4.2. K outputs

2.4.2.1. Harvested product and removed crop residue (OUTs 1 and 2)

Table 2.8 depicts yields and K contents of grain and straw at the three experimental sites in the dry season 2000-2001 and wet season 2001. Grain K content was ≤ 10 kg ha^{-1} when yield was ≤ 5 Mg ha^{-1} and about 20 kg K ha^{-1} when yield was between 6 and 7 Mg ha^{-1}. K content in straw ranged from 39-118 kg ha^{-1}, depending on K supplies and seasons. Stubble contained 12 – 50 kg K ha^{-1} per crop. On the average per Mg of grain K content in grain, straw and stubble were: 2.5, 14.4 and 7.8 respectively (Fig 2.2).

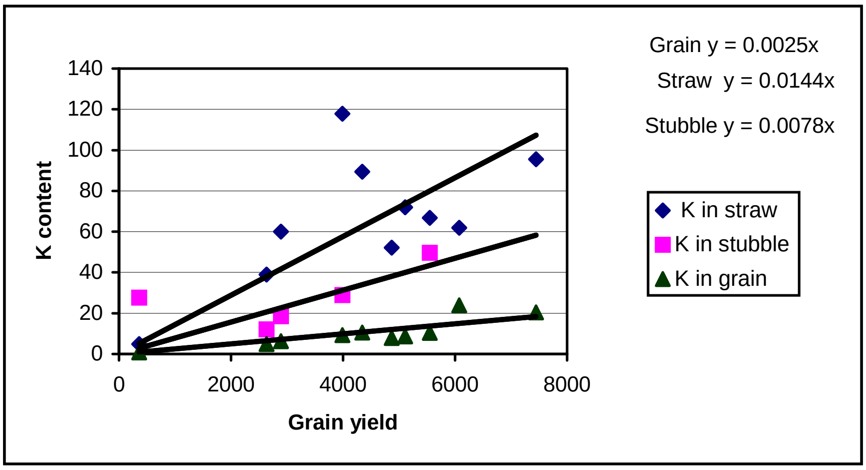

Fig. 2.2: K content (kg ha^{-1}) in straw, stubble and grain in relation to grain yield (kg ha^{-1}). Data derived from Table 2.8.

Table 2.7: Sediment input via floodwater in 2000 and 2001.

Sediment characteristics	Flood 2000			Flood 2001		
	CLLRI	An Phong	Thoi Thanh	CLLRI	An Phong	Thoi Thanh
Sediment thickness (mm)	16.6 ± 0.14	22.2 ± 2.37	30.0 ± 6.13	8.8 ± 0.42	19.8 ± 7.42	20.2 ± 1.95
Sediment weight at 40ºC (Mg ha^{-1})	39.68 ± 8.57	93.9 ± 8.24	178.38 ± 23.92	17.25 ± 0.36	76.02 ± 31.68	90.17 ± 22.42
Input of K(NH_4OAc) kg ha^{-1}	7	10	21	3	7	10
Input of K(NaTPB) kg ha^{-1}	18	40	75	11	42	59
Input of Total K ha^{-1}	710	1926	3868	320	1651	1892

Table 2.8: Grain and straw yield, K mass fraction and K content in grain and straw at the three experimental sites in the dry season 2000-01 and wet season 2001.

Crop data	CLRRI-NP plot		CLRRI-NPK plot		An Phong			Thoi Thanh		
	Dry season 00-01	Wet season 01	Dry season 00-01	Wet season 01	Dry season 00-01	Wet season 01	Ratoon crop	Dry season 00-01	Early wet season 01	Wet season 01
Grain yield (kg ha^{-1}) at 14% mowasture content	4868	2636	5109	2890	7447	3987	360	6077	5546	4345
Dried grain yield (kg ha^{-1})	4316	2337	4530	2562	6602	3535	319	5388	4917	3852
Dried straw yield	4568	4331	4370	4892	6670	6074	548	4323	5595	6246
Dried stubble yield						2733			1782	
K mass fraction in grain (g kg^{-1})	1.62	1.84	1.70	2.17	2.75	2.31	2.31	3.94	2.12	2.72
K mass fraction in straw	11.40	9.01	16.48	12.27	14.32	19.40	9.01	14.31	11.94	14.32
K mass fraction in stubble						18.2			16.2	
Grain K content (kg ha^{-1})	7.9	4.9	8.7	6.3	20.5	9.2	0.8	23.9	10.4	10.5
Straw K content (kg ha^{-1})	52.1	39.0	72.0	60.0	95.5	117.8	4.9	61.9	66.8	89.4
Stubble K content (kg ha^{-1})[a]/		*12.1*		*18.6*		49.7			28.9	*27.7*
Residue removal (kg ha^{-1})	52	27	72	41	0	68	0	0	38	62
Residue removal per year (kg ha^{-1})	79		113			68			100	
Harvested product per year (kg ha^{-1})	13		15			31			45	

[a]/Estimated stubble content at 31% of straw content in CLRRI and Thoi Thanh and at 45% in An Phong based on measured data in this study were shown in Italic.

The quantity of K removed in crop residues at the 3 sites ranged from 27 to 72 kg K ha^{-1} per crop, depending on crop residue management and K mass fraction in straw.

Amount of weed biomass growing between crops was small and all weeds were incorporated at land preparation. Therefore, there was no K output by weeds.

2.4.2.2. Leaching (OUT 3):

Table 2.9 shows that average K concentrations in the soil solution at the three sites ranged from 0.52-6.4 mg l^{-1}. Concentrations were higher at 3 days than at 20-25 days after K application, especially in the NPK plots at CLRRI in the wet season 2001. The concentrations at the two depths were highly correlated and near the 1:1 line (Fig 2.3). Therefore, the average value of K in soil solution at two depths was used to calculate K loss by leaching. Water percolation rate ranged from 0.3 mm to 1.5 mm d^{-1} (Table 2.10), which is a common range for percolation through a hardpan. Total K loss due to percolation was estimated to be small (<1-2 kg K ha^{-1}).

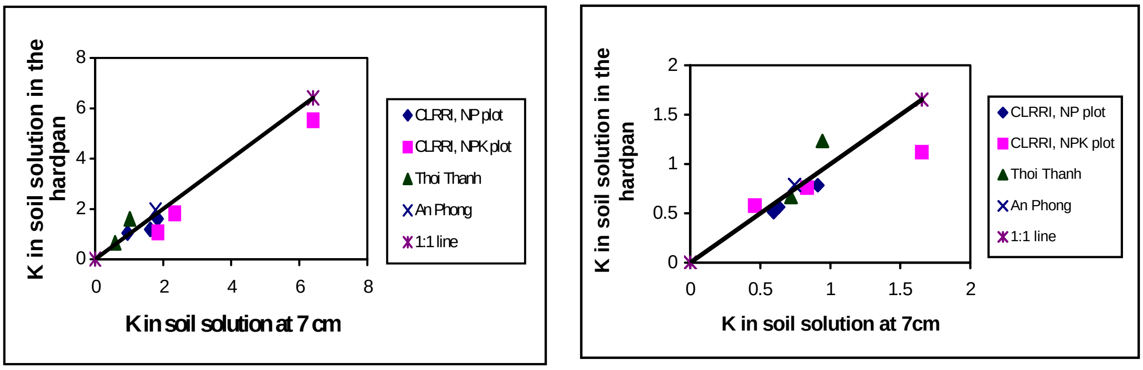

Figure 2.3: Relation between K in soil solution at 7 cm depth and in the hardpan at 3 days (left) and at 20-25 days after K application (right)..

Table 2.9: K concentration (mg l^{-1}) in the soil solution at two depths in the experimental sites.

Season	NP plot			NPK plot			An Phong			Thoi Thanh		
	at 7 cm depth	at the hardpan	average	at 7 cm depth	at the hardpan	average	at 7 cm depth	at the hardpan	average	at 7 cm depth	at the hardpan	average
Wet season 2000												
at 3 days after K application	0.96	1.05	1.00	1.84	1.07	1.46	-	-	-	-	-	-
at 20-25 days after K application	0.63	0.56	0.60	0.46	0.58	0.52	-	-	-	-	-	-
Dry season 2000-2001												
at 3 days after K application	1.62	1.19	1.41	2.34	1.83	2.08	-	-	-	0.59	0.66	0.62
at 20-25 days after K application	0.60	0.51	0.55	0.83	0.76	0.80	-	-	-	0.72	0.67	0.69
Wet season 2001												
at 3 days after K application	1.84	1.61	1.72	6.41	5.52	5.96	1.78	1.95	1.87	1.02	1.6	1.31
at 20-25 days after K application	0.91	0.78	0.85	1.65	1.12	1.39	0.74	0.88	0.81	0.94	1.24	1.09

Table 2.10: Percolation rate, average K concentration in the soil solution and K loss due to vertical percolation at the three experimental sites.

Season	Date	CLRRI[a/]		An Phong	Thoi Thanh
		NP plot	NPK plot		
		Water loss (mm day^{-1})			
	Day1	1.8 ± 1.6	1.8 ± 1.6	1.0 ± 1.3	-
Dry 00-01	Day 2	0.0 ± 0.2	0.0 ± 0.2	1.2 ± 1.0	0.5 ± 0.3
	Day 3	0.2 ± 0.4	0.2 ± 0.4	0.2 ± 0.7	0.0 ± 0.2
	Average	*0.7 ± 1.0*	*0.7 ± 1.0*	*0.7 ± 0.7*	*0.3 ±0.4*
Wet 01	Day 1	1.1 ± 0.7	1.1 ± 0.7	1.6 ± 0.6	1.7 ± 1.9
	Day 2	0.5 ± 0.1	0.5 ± 0.1	0.8 ± 0.3	1.9 ± 2.4
	Day 3	-	-	0.5 ± 0.3	0.8 ± 0.3
	Average	*0.8 ± 0.4*	*0.8 ± 0.4*	*1.0 ± 0.6*	*1.5 ±0.6*
	Average K in soil solution (mg l^{-1}) and K loss per crop (kg ha^{-1})				
Dry 00-01	3 DAK	1.41	2.08	-	0.62
	20-25 DAK	0.55	0.80	-	0.69
	K loss[b/]	0.3	0.6	-	0.2
Wet 01	3 DAK	1.72	5.96	1.87	1.31
	20-25 DAK	0.85	1.39	0.81	1.09
	K loss[b/]	0.7	1.1	0.8	1.6

[a/] Water losses in NPK plot were applied for NP plot as well.

[b/] Calculation was based on K in soil solution at 20-20 DAK (days after K application) and on a crop cycle of 100 days.

2.4.2.3. Sediment loss (OUT 4).

The mass fraction of sediment in drainage water after soil puddling at Thoi Thanh was 1.8 g l^{-1}. With 30 mm of drainage water, or 300 m^{3} per ha, a total of 540 kg sediment was lost, containing 0.063, 0.23 and 11.7 kg ha^{-1} of K(NH$_4$OAc), K(NaTPB) and K(total), respectively, for each crop (based on values of K fractions in sediment 2000 in Thoi Thanh) . These losses were of little importance for the K balance.

Sediment may be removed by farmers to facilitate gravity irrigation. The sediment removal at Thoi Thanh was calculated based on information on size and depth of canals, and time of sedimentation obtained from farmer's interviews (Table 2.11). At the Thoi

Thanh field, the farmer removed sediment from an area of 2500 m^2 into two canals. One canal along the width of the field (25 m long, 1.5 m wide at top, 1 m wide at bottom and 1 m depth) was half-filled after 3 years and the other canal along the length of the field (100 m long, 1m wide at top, 0.5 m wide at bottom and 0.6 m depth) was filled completely after 3 years. This practice indeed causes a significant loss of sediment. It was estimated at 36% of the sediment deposition in Thoi Thanh in year 2001. Therefore, also 36% of K(NH_4OAc), K(NaTPB) and K(total) was removed. No data on sediment removal were collected in An Phong. Our impressions from field inspections suggest that farmers' practices were similar in An Phong and Thoi Thanh. Therefore, K loss by sediment removal in different forms was also estimated at 36% of K input via sedimentation. At CLRRI, where sediment deposition was low and no obvious sediment removal took place in practice, it was assumed that no K was leaving the field in this way.

Table 2.11: Estimation of sediment loss by removal during leveling the field surface at Thoi Thanh.

Data on sediment loss	Value
Half of volume of canal 1 (25 x (1.5+1)/2 x 1)/2	15.6
Volume of canal 2 (100 x (1+0.5)/2 x 0.6)	45.0
Volume of sediment in 2500 m2 after 3 years	60.6
Volume of sediment removed (m3 ha-1 year $^{-1}$)	80.8
Sediment wet bulk density (g cm-3)	0.39
Dried sediment removed (Mg ha $^{-1}$ year $^{-1}$)	32
Dried sediment at Thoi Thanh 2001 (Mg ha $^{-1}$year $^{-1}$)	90
Sediment loss (%)	36
K loss as K(NH_4OAC) (kg ha^{-1} year^{-1})	4
K loss as K(NaTPB) (kg ha^{-1} year^{-1})	21
K loss as K total (kg ha^{-1} year^{-1})	681

2.4.3. K budgets in double and triple rice crops systems

Because straw management was different in each crop, and input by rain water and sediment deposition was annual, the final budget was calculated on an annual basis.

2.4.3.1 Double cropping with little sediment deposition, high residue removal, and no or high K fertilizer application (CLRRI).

In this system, annual input via rainwater and irrigation water together was 24 kg ha^{-1} (Table 2.12). This amount was higher than the input of K(NH4OAC) and K(NaTPB) by sedimentation, because of the low sedimentation rate in this area. Input by sediment was more important if K(total) was considered. However, not all K of this K form is beneficial to plants over relatively short periods of time. Among the outputs, crop residue removal was the largest (79 -113 kg ha^{-1}), representing 85-87% of the sum of outputs 1, 2 and 3. BAL(soluble K) was negative (-69 kg), when no fertilizer K was applied.

Because the input of K(NH_4OAc) and K(NaTPB) via sedimentation was low (3-11 kg K ha^{-1}) and rice straw was mostly removed, the balance of K(NH4OAc) and K(NaTPB) was also negative when no K fertilizer was applied, but the balance of K(total) was positive (Table 2.12). In the NP plot, rice has been grown for 12 consecutive crops without K application. K mass fraction in straw was low (Table 2.8), but the yield difference of about 250 kg ha^{-1} between NPK and NP treatments was not statistically significant. Obviously, the soil was being mined for K, especially K in non-exchangeable forms, but not yet to an extent that would cause significant yield loss.

The NPK plot received 75 kg K ha^{-1} per crop. This high K application resulted in a positive balance in all three forms of K (Table 2.12). Although rice straw was removed in this system, fertilizer K was enough to compensate for K removed by grain and straw. Hence, addition of K via K fertilizer can be an option to balance the K removal via harvests. Rice straw recycling to the field is another option, which is also beneficial in terms of N and P recycling.

2.4.3.2. Double crop with much sediment deposition, residue incorporation and moderate K fertilizer application (An Phong).

In An Phong, some rice straw remained in the field. As a result K removed via crop residues was less than in CLRRI, though K removal via grain was about twice as large than in CLRRI (Table 2.12). The reduction in output together with an average application of 70 kg K ha^{-1} per year as fertilizer and 42 kg ha^{-1} in the form of K(NaTPB) in sediment, resulted in a positive annual K balance of K(NaTPB). The balance was slightly negative for K(soluble) (-7 kg ha^{-1}) and for K(NH_4OAc) (-3 kg ha^{-1}), and was strongly positive for K(total).

2.4.3.3. Triple cropping with much sediment deposition, residue incorporation and low K fertilizer application (Thoi Thanh).

In Thoi Thanh, sediments supply more K(NH_4OAc), K(NaTPB) and K(total) than at the two other sites (Table 2.12). Three rice crops were grown per year, and the K removal by crops was high while inputs via K fertilizer addition were small. This resulted in a negative balances for K(soluble), K(NH_4OAc) and K(NaTPB), but in positive balance for K(total).

Although triple cropping systems with low sediment deposition have not been investigated, based on the above observation and with the current practice of rice straw management, it is clear that the K balance in such situations will be highly negative for K(soluble), K(NH_4OAc) and K(NaTPB).

2.4.4. Comparison between complete and partial budgets

Table 2.13 shows K balances for the four systems discussed before, when applying a partial budgeting approach similar to the one used by Dobermann et al. (1996c). In this approach, it is assumed that inputs from rain water, irrigation and sediments equal the losses due to percolation and seepage, or in other words the balance is made up of inputs via K fertilizer minus outputs via harvested product and removed crop residues only.

Table 2.12: Annual K budgets in double and triple rice cropping system in CLRRI, An Phong and Thoi Thanh. All values were in kg ha^{-1} year^{-1}.

Budget/balance	**K flux**	**NP plot**	**NPK plot**	**An Phong**[a/]	**Thoi Thanh**
	Input/Output				
Soluble K	Chemical fertilizer	0	150	70	40
	Rain water	6	6	10	6
	Irrigation water	18	18	14	15
	Total input (INs1,2,3)	24	174	94	61
	Harvested product	13	15	31	45
	Removed crop residues	79	113	68	100
	Leaching	1	2	2	2
	Total output (OUTs1,2,3)	93	130	101	147
	BAL(soluble K)	**-69**	**44**	**-7**	**-86**
K(NH_4OAc)	Sediment in flood water	3	3	7	10
	Total input (INs 1,2,3,4)	27	177	101	71
	Sediment loss	0	0	3	4
	Total output (OUTs1,2,3,4)	93	130	104	151
	BAL(KNH_4OAc)	**-66**	**47**	**-3**	**-80**
K(NaTPB)	Sediment in flood water	11	11	42	59
	Total input (INs 1,2,3,4)	35	185	136	120
	Sediment loss	0	0	15	21
	Total output (OUTs1,2,3,4)	93	130	116	168
	BAL(KNaTPB)	**-58**	**55**	**20**	**-48**
K (Total)	Sediment in flood water	320	320	1651	1892
	Total input (INs 1,2,3,4)	344	494	1745	1953
	Sediment loss	0	0	594	681
	Total output (OUTs1,2,3,4)	93	130	695	828
	BAL (K Total)	**251**	**364**	**1050**	**1125**

[a/] Sediment loss in An Phong was also estimated at 35 % of input by sediment; just as calculated for Thoi Thanh area. (1996).

Table 2.13: Comparison of partial and complete K budgets at the experimental sites.

Input/Output	**NP plot**	**NPK plot**	**An Phong**	**Thoi Thanh**
Chemical fertilizer	0	150	70	40
Total input	*0*	*150*	*70*	*40*
Harvested product	13	15	31	45
Removed crop residues	79	113	68	100
Total output	*92*	*128*	*99*	*145*
Balance of partial budget	**-92**	**22**	**-29**	**-104**
Balance(soluble) of complete budget	**-69**	**44**	**-7**	**-86**
Difference between complete and partial budget	23	22	22	18

Results indicate that the differences in the balance estimates for K(soluble) between the two approaches ranged between 18 and 23 kg ha^{-1}. The difference was significant and was due to the fact that inputs via rain water and irrigation water were not equal to losses due to percolation and seepage. K input by rain water and irrigation water contributed a total of 21-24 kg K ha^{-1} year^{-1}, while K loss by percolation was only 1-2 kg ha^{-1} year $^{-1}$ (Table 2.12). From this comparison, we conclude that K balances of rice cropping systems should also include inputs via rain water, irrigation water and sedimentation, and output via leaching.

2.5. Discussion and Conclusions

Our data on K concentrations in rain and irrigation water; and rates of sedimentation and percolation were comparable to those found by others (Table 2.14). Rain water and irrigation water did supply K to the field. Therefore, these inputs need to be included in K budget studies of rice cropping systems. Newly deposited sediments

Table 2.14: Comparison of rates of K concentrations in rain and irrigation water, and of sedimentation and percolation as found in the current study and in other studies.

Type of data	Values found in this study	Values found in other studies	Source
K in rain water (mg l^{-1})	0.3 – 3.3	0.35 – 0.39	Handa (1988), Abedin Mian et al., (1991)
K in irrigation water (mg l^{-1})	1.5 - 2.5	1 – 5	Handa (1988), Kawaguchi and Kyuma (1977), Abedin Mian et al. (1991)
Sediment in irrigation water (mg l^{-1})	11-500	21- 322	Nga (2001)
Wet sediment thickness, mm	16-30	7- 68	Nga (2001)
Percolation rate, mm d^{-1}	0.3 – 1.5	0.1- 10[a/]	Greenland (1985), Hardijoamidjojo (1992), Shamar & De Datta (1992), Humphreys et al. (1992), Tuong et al. (1994), Jo and Um (1990), Dobermann (1996)
		neglible	Sekhon (1976)

a/ In sandy soils much higher rates were found

from irrigation and flooding supplied small amounts of K(NH4OAc) and K(NaTPB), but relatively large amounts of mineral K depending on the rate of sedimentation, suggesting that inclusion of this input in the calculation of K budgets is also needed. The relevant question is now, in which term the mineral K is transferred into K(NaTPB) and K(NH_4OAc) and hence becomes available to the rice crop. In areas with more than 100-200 ton sediment per ha per year in the triple cropping system like in Thoi Thanh, the balance was negative for K(NH4OAc), but less negative for K(NaTPB). Evidently, the differentiation between available and non-available K is important, especially when the inputs of initially non-available forms can supply substantial amounts of K to the plants.

Removal of straw residues formed a major output of K (Table 2.12). Other outputs were relatively small, except when farmers remove sediment to allow gravity irrigation. Percolation loss in these clay soils was small, because of the presence of hardpans and the puddling practice. Losses via leaching may be neglected for clay soils, but not for soils with coarse texture. This was reflected in the very wide range of percolation rates (Table 2.14) published in the literature (Greenland, 1985; Jo and Um, 1990; Hardijoamidjojo, 1992; Sharma and De Datta, 1992; Humphreys et al. 1992b; Tuong et al., 1994).

In conclusion, the partial budgeting approach as used by many authors (e.g. Patnaik, 1978; Bajwa, 1993; Dobermann, 1996) was inadequate for accurate estimation of the K balance for rice cropping systems in the Mekong Delta. Moreover, previous estimations refer only to available K, and thereby result in unnecessary negative balance warnings. The complete budgeting approach is needed to obtain a correct evaluation of the K balance of the rice cropping systems. Inputs via rain water, irrigation water and sedimentation, and output via leaching and sediment removal should be included in budgets, either measured or estimated.

Differentiation between available and non-available K is important in identifying unbalances in K. Whether K fertilizer is needed to meet the short-term plant demand for yields of 6-7 Mg ha^{-1}, depends on the rate of release of mineral K from soil and freshly deposited sediment. Even with high sediment deposition rates, K balances were negative for K(soluble), K(NH_4OAC) and K(NaTPB).

Double cropping systems had slightly positive K balances, when small amounts of K fertilizer are added and rice straw was not removed from the field. Triple cropping systems are predicted to have more negative K balances than double cropping systems.

Negative balances for K(soluble), K(NH_4OAc) and K(NaTPB), and highly positive balances for Total K stress the need for studying the release of available K from non-available forms. Whether or not fertilizer K will be needed, depends on the rate of transfer of K from the non-available (mineral) pools to the available pools. This will be discussed further in Chapters 4, 5 and 6.

Annex 2.1: Analytical procedures for determination of soil K fractions

0.01 M $CaCl_2$ extraction for soluble K:

A half gram of air-dried soil was placed in a 50 ml (ratio of air-dried soil:solution of 1:10) polyethylene centrifuge tube with cover. Five ml 0.01M $CaCl_2$ solution were added to the tube and the suspension was shaken in a reciprocal shaker for 30 min. Soil solution was then filtered and collected for K measurement by Atomic Absorption Spectrophotometer. The measurement was carried out in a 1 ml aliquot of sample in a test tube with 1 ml of 3 M HCl, 0.5 ml of 5000 mg l^{-1} CsCl solution, and 2.5 ml deionised water (if sample was diluted 5 times). For other dilution samples, the same ratio of HCl to CsCl was used.

1 M NH_4OAc pH7 extraction for exchangeable K

A half gram of air-dried soil was placed in a 50 ml polyethylene centrifuge tube with cover. Ten ml of NH_4OAc 1M pH7 were added to the sample, and the suspension was shaken for 1 hour. The suspension was then filtered and collected for K determination by atomic absorption by spectrophotometer as described for K measurement in the extraction for K($CaCl_2$).

1 M boiling HNO_3 for non-exchangeable K

Two and a half grams of air-dried soil was put into 125 ml Erlenmeyer flask. 25 ml of 1M HNO_3 was added, and the flask was placed on a temperature-adjusted hotplate.

When boiling started (after 5 min), temperature was reduced, and the suspension was boiled gently for 10 min. The suspension was then filtered and the soil on the filter washed with four 15 ml portions of 0.1M $HNO_{3.}$ The filtrate was collected in a 100-ml volumetric flask. The solution was cooled, diluted and mixed thoroughly. K was determined by atomic absorption spectrophotometer using CsCl to reduce ionization of K.

0.2 M Sodiumtetraphenylborate method

A sample of 0.5 soil was weighed into centrifuge tubes and 3 ml of extracting solution (0.2 M $NABPh_4$ + 1.7 M NaCl + 0.01 M EDTA) was added. After an incubation period, 25 ml of quenching solution (0.5 M NH_4Cl + 0.11 M $CuCl_2$) was added to the tubes to stop K^+ extraction. The tubes were placed in a digestion block on a hot plate at 150^0 C until the precipitates was dissolved completely (30-45 min). The suspension in the tubes was diluted to 50 ml with deionized water, mixed, then left undisturbed for 30 min to allow the soil to settle. A 20 ml aliquot of the supernatant was poured into 50 ml centrifuge tubes containing three drops of 6 M HCl and was centrifuged at for 5 min. The acidification of the extract helps to prevent precipitation of Cu^{2+} and the breakdown product of NaTPB, if extracts need to be stored for longer than 1 d. The extract was diluted (1:10) with deionized water and K^+ was determined by atomic absorption spectrophotometry. In my study, 0.2 ml of HCl 6 M was used instead of three drops of 6 M HCl, because of quick precipitation of Cu^{2+}.

Total K

Total K was determined using HF-$HClO_4$ digestion following the procedure of Jackson (1958), as described by Page et al. (1982). One-gram of air-dried soil was placed into a platinum crucible. Soil was moistened with a drop or two of deionized water, then five-ml of HF and 0.5 ml of $HClO_4$ were added. The crucible was covered and heated at 200°C until acid had been evaporated using a sand bath. Sample was left to cool. Then, 5 ml of 6 M HCl and 15 ml deionized water were added. The sample was again placed in a hot plate and was gently boiled for 5 min., till the soil was completely digested. When the sample showed traces of soil solids, the procedure was repeated, by adding 5-ml of HCl and 0.5 ml of HF.

CHAPTER 3

EVALUATION OF METHODS FOR CHEMICAL FRACTIONATION OF SOIL K

3.1. Introduction

The ability of soils to supply K to plants depends on K in solution, exchangeable K and a substantial amount of non-exchangeable K (Barber and Mathews, 1962; Richards et al., 1988; Mengel and Uhlenbecker, 1993; Rahmatulla et al., 1994). These forms or fractions are supposed to be related to each other, for example according to the reactions depicted in Fig. 3.1. In this view, the availability of K to plants is a result of a chain of reactions.

Many attempts have been made to find the best method for measuring plant-available K, using different extraction solutions, such as 0.01 M $CaCl_2$, 1 M NH_4OAc at pH 7, 1 M HNO_3 and 0.2 M NaTPB. In many countries, 1 M NH_4OAc is considered the best option for routine soil testing purposes, but it has been clearly demonstrated that this extraction solution is inadequate for illitic soils (McLean, 1976; Portela, 1993; Eckert and Watson, 1996) and vermiculitic soils (Cassman et al., 1990). NH_4OAc-extractable K was also a poor indicator of plant-available K in kaolinitic soils (Dobermann et al., 1996b, Nair et al., 1997; Cox et al., 1999).

It is questionable whether a single extraction can suffice for a predictive understanding of K availability. The use of a series of extractions rather than a single extraction, in combinations with modeling may provide better information for a quantitative prediction of soil K availability. Very few studies have investigated the suitability and reliability of extraction methods for the determination of the different K pools and transformation coefficients in a model. Such studies are needed for the

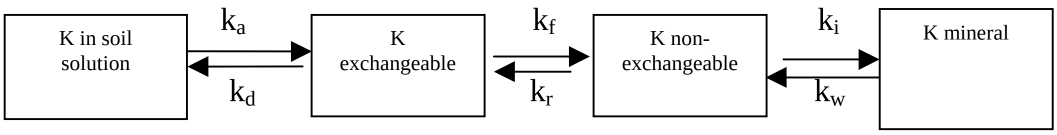

Figure 3.1. Kinetic reactions between soil K pools. The rate coefficients refer to adsorption (k_a), desorption (k_d), fixation (k_f), release (k_r); immobilisation (k_i) and weathering (k_w). Adapted from Selim et al.(1976)

development and testing of models that can predict short- and long-term K dynamics in soil.

Simulation models for nutrients dynamics in soils usually consider various nutrients pools, which differ in bio-availability. For K in soils, models usually distinguish three or more pools (e.g. Selim et al., 1976). In a four-pools model, the first pool (K1 or very labile K) is supposed to be the K found with 0.01 M $CaCl_2$ solution (Houba et al., 1986; Van Erp ,2002), which extracts K in the soil solution and part of exchangeable K. The 1 M NH_4OAc pH7 solution extracts both solution and exchangeable K, and was reported to be related closely to K uptake by a crop (Pratt, 1951; Pearson, 1952; Eagle, 1967; Goulding, 1987; Hoa et al. 1998). The difference between K(NH_4OAc) and K($CaCl_2$) is then assumed to be the second pool (K2 or labile K). Clearly, both $CaCl_2$ and NH_4OAc extract K in solution and (some) exchangeable K, and the first two pools of labile K may be combined, for reasons of convenience. In this study, we made no attempt to distinguish soil solution K as a separate pool. Hence, we consider here a three-pools model with one pool of labile K consisting of both solution K and exchangeable K.

The second main pool in the sequence is of particular interest in assessing the sustainability of K supply. Possible candidates for assessing this pool are boiling 1 M HNO_3, 3 M HNO_3, and sodium tetra-phenyl borate (NaTPB) of different concentrations and at different incubation periods. A solution of 1 M NaCl-0.067M NaTPB was first investigated by Scott et al. (1960), and Scott and Reed (1962). In a later development Smith and Scott (1966) used it to remove all naturally occurring non-exchangeable K in minerals and soils. They found that large amounts of K can be removed by using a long extraction period of up to 60 days. Table 3.1 summarises the studies on different NaTPB extraction procedures for determining non-exchangeable K. Among the various extraction periods for 0.2 M NaTPB, a period of 5 minutes was suggested to be more practical than periods of 1 or 15 minutes (Cox et al., 1999). The difference between K(NaTPB) and K(NH_4OAc) is assumed to be the second main pool.

Total K can be analysed by digestion with a mixture of concentrated HF and $HClO_4$; the difference between K(total) and K(Na TPB) is considered to be the third pool (K mineral).

The above-described analytical methods for the characterisation of various soil K pools have not yet been tested for soils in the Mekong Delta. Because one of the major aims of this study was to develop a model for predicting short- and long-term K supplies in soil, it is necessary to develop adequate analytical methods for the assessment of the various soil-K pools. The laboratory experiments described in this chapter deal with 0.01 M $CaCl_2$, 1 M NH_4OA_C at pH 7, 1 and 3 M HNO_3, NaTPB extractions, and with total K analyses. The investigations can be subdivided into a preliminary and a main part. In the preliminary part, five soils were used to test a wide range of concentration of K(NaTPB) and extraction times. These five soils were also included in the main part, in which all together 19 soils were studied, representative for the most important soils in the Mekong Delta. The results of both studies were compared with the uptake of K by rice in a pot experiment.

Table 3.1: Summary of studies on different NaTPB extraction procedures for determining non-exchangeable K.

Concentration of NaTPB	Incubation period	Duration of growth	Reference
0.3 M	15 min	10 weeks	Schulte and Corey (1964)
0.3 M	1 hour	54 weeks	Wentworth and Rossi (1972)
0.2 M	5 min	2-20 crops (28 days per crop) until soil became K-deficient	Cox et al., 1999
0.03 M	16 hours		Jackson, 1985

The objective of the preliminary study was to find the NaTPB extraction procedure that best described the K supply to plants from the first two pools in a three pools model. The objectives of the main study were to investigate the potential and the reliability of the 0.01 M $CaCl_2$, 1 M NH_4OAC pH 7, 1 M and 3 M HNO_3, the selected NaTPB extraction procedures, and total K analysis for the characterisation of the pools in a three- pools model.

3.2. Materials and Methods

3.2.1. Greenhouse exhaustion experiment

A pot experiment was carried out in the greenhouse of the Can Tho University with 19 soils (described in Section 3.2.3), with 3 replicates for each soil. Pots were filled with one kilogram (air-dried basis) of soil that had passed a 20 mm-sieve. Twenty-five rice plants were grown in each pot, in total 3 rice crops in succession, each with duration of 5 weeks. Fertiliser N and P were applied at rates of 200 mg N and 50 mg P for each crop. N was applied three times at 0, 15 and 25 days after sowing. P was applied 1 day before sowing. Hoagland and Arnon solution No. 2 (F.B.Salisbury and C. W.Ross, 1992) was diluted 10 times and applied each week during each cropping period. No fertiliser K was applied. At each harvest, the above-ground plant parts were taken after each crop, oven-dried at 70^{o}C, weighed, ground, and analysed for K. The roots remained in the pots. K uptake was calculated as the product of dry mass and K mass fraction. Uptake of K from the soil was calculated as total K uptake minus K in seeds. The K content in 25 seeds was estimated at 0.038 mmol. (The average mass fraction of K in grains, as estimated from the 3 sites in Table 2.7, was set at 2.35 g kg^{-1}, and the mass of 1000 grains at 25 g.). Soil samples were taken for the analysis of K fractions at the beginning of the first crop and after the harvest of the third crop.

3.2.2. Laboratory studies

3.2.2.1. Preliminary study on extractions with NaTPB

Two variables of the NaTPB extraction procedures were tested: duration of extraction and concentration of the NaTPB solution. Five treatments were included: 0.067 M NaTPB at 1, 5 and 15 minutes extraction time, and 0.2 M NaTPB at 1 and 5 minutes extraction time. Five soils (Section 3.2.3) were used. The amounts of K extracted were compared with the K uptake from the soil in the exhaustion experiment.

3.2.2.2. Main study on K fractionation

The methods for extraction of soil K fractions have been described in Annex 2.1. The extraction solutions were 0.01 M $CaCl_2$, 1 M NH_4OAc pH 7 (1 hour shaking), boiling 1 M HNO_3 and 0.2 M NaTPB in 5 min. The last one was chosen on the basis of the results of the preliminary study. Soils were analysed at the beginning and at the end (after 3 crops) of the exhaustion experiment described above.

Also, boiling 3 M HNO_3 was used as extraction solution, to test whether the extraction power of HNO_3 increases with an increase in acid concentration. The procedure of extraction was similar to the one used with boiling 1 M HNO_3.

Total K was determined by a $HClO_4$-HF acid mixture.

3.2.3. Description of the soils

All together, 19 soils were used in the greenhouse and main laboratory studies (Tables 3.2 – 3.4). In the preliminary study, only Soils 2, 6, 9, 12 and 17 (Tan An, Chau Phu, CLRRI-NP, Binh Phu and Cau Ke) were used; they represent a wide range of K(NaTPB) and soil textures.

Table 3.2 lists the sites, cropping intensity and practices of K application. Soils have been classified (Table 3.3) following the FAO-UNESCO classification system (FAO, 1998). Soil texture is given in Table 3.3, and chemical characteristics are shown in Table 3.4.

Table 3.2. Rice cropping intensity and K fertilisation (kg K ha^{-1} per crop) in the fields of the sampled soils.

Soil number	Site	Crops per year	K fertilisation
1.	Cang Long -TV	2	25 *
2.	Tan An - LA	3	25 *
3.	Cho Moi - AG	2	-
4.	Chau Thanh - KG	2	10
5.	Cai Lay - TG	3	25 *
6.	Chau Phu - AG	3	10
7.	CLRRI- NP plot	2	0
8.	2 CLRRI – NPK plot	2	75
9.	2 CLRRI – NP plot	2	0
10.	Thoai Son - AG	2	10
11.	Vinh Trinh -TN-CT	2	25
12.	Binh Phu -MH - LA	2	25-50**
13.	Vinh Hung-MH-LA	2	25-50**
14.	Tan Chau (Trang)	2 + 1 upland crop	7
15.	Tan Chau (Bon)	2 + 1 upland crop	25
16.	Tan Chau (Tho)	2 + 1 upland crop	10
17.	Cau Ke - TV	2	25
18.	An Cu - AG	1	0
19.	Go Tranh-MH-LA	2	25**

* These fields belonging to the provincial agriculture extension service, receive K fertiliser according to the current recommendation for rice (25kg ha^{-1}).

** These fields are old alluvial soils and farmers realise the importance of K fertiliser in these soils.

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Table 3.3. Classification (FAO, 1998), particle size distribution and texture class of the soils.

Soil number	Site	FAO-UNESCO classification	Sand	Silt	Clay	Texture class
				g kg^{-1}		
1.	Cang Long -TV	Mollic Gleysols	13	416	572	Clay
2.	Tan An - LA	Dystric- Gleyic Luvisols	39	411	550	Clay
3.	Cho Moi - AG	Dystric Fluvisols	8	405	587	Clay
4.	Chau Thanh - KG	Umbric Endo Prothothionic Gleysols	87	379	533	Clay
5.	Cai Lay - TG	Humic-Mollic- Gleysols	152	327	521	Clay
6.	Chau Phu - AG	Fluvic-Dystric- Gleysols	10	416	574	Clay
7.	CLRRI- NP	Fluvic- Mollic-Gleysols	7	408	586	Clay
8.	2 CLRRI – NPK [a/]	Fluvic- Mollic-Gleysols	6	393	601	Clay
9.	2 CLRRI – NP [a/]	Fluvic- Mollic-Gleysols	6	393	601	Clay
10.	Thoai Son - AG	Humic-Umbric Gleysols	8	396	596	Clay
11.	Vinh Trinh -TN-CT	Dystric - Gleysols	8	503	490	Silty clay
12.	Binh Phu -MH - LA	Humic Plintosols	81	381	538	Clay
13.	Vinh Hung-MH-LA	Dystric Plintosols	58	396	546	Clay
14.	Tan Chau (Trang)	Dystric Fluvisols	40	572	388	Silty clay loam
15.	Tan Chau (Bon)	Dystric Fluvisols	12	595	393	Silty clay loam
16.	Tan Chau (Tho)	Dystric Fluvisols	84	643	273	Silty clay loam
17.	Cau Ke - TV	Gleyic Dystric Arenosols	498	346	156	Loam
18.	An Cu - AG	Haplic- Arenosols	809	188	3	Loamy sand
19.	Go Tranh-MH-LA	Aruptic Plintosols	379	529	92	Silt loam

[a/] The 2CLRRI-NPK and 2CLRRI-NP are soils from treatments in the second long-term NPK fertiliser experiment at CLRRI.

Table 3.4. Chemical characteristics of the soils.

Soil no.	Site	pH $_{H20}$ (1:1)	EC (1:5) mS cm^{-1}	Organic C g kg^{-1}	CEC and exchangeable cations[a/] ($mmol_c$ kg^{-1})					
					CEC	K	Ca	Mg	Na	K/CEC(%)
1	Cang long	4.5	0.4	79.99	177.3	4.3	30.2	30.6	9.4	2.45
2	Tan An	4.1	0.6	18.45	169.4	4.0	23.1	31.6	1.6	2.38
3	Cho Moi	4.8	0.4	15.66	137.9	3.6	39.3	23.9	5.6	2.64
4	Chau Thanh KG	4.1	0.6	57.66	127.4	3.4	18.4	30.6	12.9	2.68
5	Cai Lay	4.9	0.7	12.47	225.4	2.7	52.2	33.2	9.0	1.19
6	Chau Phu	5.0	0.3	16.07	147.6	1.8	42.3	22.8	3.9	1.25
7	CLRRI- NP plot	4.5	0.6	36.43	199.2	1.5	50.5	33.2	2.8	0.78
8	2CLRRI-NPK plot	4.4	0.6	30.10	195.4	1.7	40.9	32.0	4.2	0.89
9	2CLRRI-NP plot	4.3	0.5	32.42	185.2	1.7	41.6	32.8	3.3	0.91
10	Thoai son	4.2	0.6	24.13	170.6	1.4	34.9	32.6	4.4	0.81
11	Vinh Trinh	4.7	0.4	14.27	140.9	1.2	41.6	23.8	3.7	0.87
12	Binh Phu MH	4.1	0.3	30.80	98.5	1.3	13.7	14.5	7.3	1.30
13	Vinh Hung MH	4.2	0.3	42.75	90.2	1.0	15.1	13.7	4.5	1.11
14	Tan Chau Trang	5.4	0.2	15.26	147.4	1.1	41.1	22.2	2.9	0.72
15	Tan Chau Bon	5.5	0.1	14.85	119.6	1.0	42.9	22.4	2.3	0.86
16	Tan Chau Tho	5.7	0.1	11.08	119.6	0.8	35.6	19.6	1.5	0.71
17	Cau Ke	4.7	0.2	19.43	52.3	0.9	18.0	14.4	3.6	1.69
18	An Cu	5.3	0.1	5.68	13.5	0.7	8.5	1.8	0.4	5.26
19	Go Tranh	4.4	0.1	8.70	23.9	0.5	7.7	3.8	0.3	2.18

[a/] Exchangeable Ca, Mg, Na were measured in $BaCl_2$ unbuffered extracting solution which was used in CEC determination. Exchangeable K was analysed by 1M NH_4OAc pH7,

Table 3.5. Average dry matter yield, mass fraction of K and uptake of K by the three successive crops.

Soil No.	Site	Average dry matter (g per kg soil)				Average mass fraction of K (g per kg crop DM)			Average uptake from soil (mmol per kg soil)			
		Crop 1	Crop 2	Crop 3	3 crops	Crop 1	Crop 2	Crop 3	Crop 1	Crop 2	Crop 3	3 crops
1.	Cang Long -TV	10.3	9.1	10.1	29.6	10.42	8.76	4.59	2.73	2.01	1.16	5.90
2.	Tan An - LA	14.3	9.9	10.0	34.2	18.60	10.07	5.09	6.78	2.51	1.28	10.58
3.	Cho Moi - AG	15.3	9.5	10.3	35.1	14.53	6.50	4.25	5.66	1.54	1.09	8.29
4.	Chau Thanh - KG	9.8	9.7	10.0	29.5	16.75	9.89	5.03	4.20	2.42	1.25	7.87
5.	Cai Lay - TG	13.3	9.5	6.0	28.8	14.44	11.11	4.74	4.88	2.69	0.68	8.24
6.	Chau Phu - AG	12.5	9.6	9.3	31.3	11.25	8.11	4.60	3.54	1.92	1.05	6.51
7.	CLRRI- NP plot	10.4	9.3	8.3	28.0	9.84	4.54	4.61	2.61	1.04	0.94	4.59
8.	2 CLRRI – NPK plot	10.6	8.3	7.6	26.5	8.04	4.93	5.08	2.15	1.01	0.96	4.11
9.	2 CLRRI – NP plot	10.5	7.6	7.3	25.4	5.09	5.10	4.52	1.33	0.97	0.80	3.10
10.	Thoai Son - AG	11.3	8.8	7.6	27.7	7.07	6.95	4.96	2.00	1.53	0.92	4.46
11.	Vinh Trinh -TN-CT	8.7	7.9	8.2	24.8	4.57	5.16	3.90	0.98	1.00	0.78	2.76
12.	Binh Phu -MH - LA	11.2	6.5	4.9	22.6	3.74	2.30	3.67	1.04	0.34	0.42	1.80
13.	Vinh Hung-MH-LA	9.1	4.2	4.3	17.6	2.93	1.92	3.31	0.65	0.17	0.32	1.14
14.	Tan Chau (Trang)	8.8	6.5	8.0	23.2	7.00	4.29	3.74	1.58	0.67	0.72	2.98
15.	Tan Chau (Bon)	7.8	6.3	8.3	22.4	6.02	5.53	4.14	1.17	0.86	0.84	2.87
16.	Tan Chau (Tho)	6.4	6.6	8.9	22.0	5.15	5.00	4.28	0.81	0.81	0.94	2.56
17.	Cau Ke - TV	10.2	6.4	4.9	21.5	3.88	2.46	3.36	0.97	0.36	0.38	1.72
18.	An Cu - AG	8.5	4.0	2.6	15.1	5.20	2.11	4.05	1.09	0.18	0.23	1.50
19.	Go Tranh-MH-LA	4.6	3.3	2.2	10.1	3.33	2.55	4.17	0.35	0.18	0.19	0.73

The following remarks can be made about the soils:

Soils 1 to 4 (Cang Long, Tan An, Cho Moi, Chau Thanh) are high in exchangeable K, which is attributed to intrusion of brackish water in the dry season of some years (Cang Long and Chau Thanh), and in Tan An and Cho Moi also to frequent rice straw burning.

Soils 5 to 9 (Cai Lay, Chau Phu, 3 CLRRI soils) are all in the common range of exchangeable K and other chemical characteristics (pH, Organic C, CEC) in recent alluvial soils in the Mekong Delta.

Soils 10 and 11(Thoai Son, Vinh Trinh) were selected as recent alluvial soils with low exchangeable K. Thoai Son soil is affected by acid condition in the surrounding area. Vinh Trinh is a silty clay soil.

Soils 12 and 13 (Binh Phu and Vinh Hung) are old alluvial soils. Rice crops grown in this grey soil showed good response to K fertilizer. Farmers in this area often apply 25-50 kg K ha^{-1} per crop. Rice yield is often about 3.5-4.5 Mg ha^{-1} (farmers' interview at Binh Phu and Vinh Hung). Unlike recent alluvial soils with mainly illite in the clay fraction (Section 1.4.1), these soils contain mainly kaolinite in the clay fraction.

Soils 14 to 16 (Tan Chau Trang, Tan Chau Bon, Tan Chau Tho) located in an island between two branches of the Mekong river, have been formed by deposition of coarser sediment, resulting in a silty clay loam texture. Uehara (1974) reported that silt fraction of Mekong River sediment consists for about 50% of mica. Therefore, these soils may contain much interlayer K in the silt fraction.

Soil 17 (Cau Ke) is located at the feet of the sand-bars. Therefore, its soil texture class is loam.

Soil 18 (An Cu) is a loamy sand soil with low rice yields. Farmers in this area are very poor. They often apply cattle manure at rates of 0.5-1 ton ha^{-1}, but little chemical fertilisers.

Soil 19 (Go Tranh) is a silt loam soil. Farmers are aware of the importance of K fertiliser for rice yield in this area.

3.3. Results and Discussion

3.3.1. Greenhouse exhaustion experiment

Table 3.5 presents the results of the greenhouse experiment. In Soil 1 (Cang Long), growth of the first rice crop was negatively affected by the high salinity of the soil. The second and third crops behaved normally. Therefore, Cang Long soil is considered as an outlier, and is not included in the examining of the relations between soil K and K uptake by the rice crop.

The general picture is that of declining yields and K mass fractions, and by that declining K uptake by the successive crops. Crop 3 had K mass fractions of around 3 to 4 g kg^{-1} in most soils, a value apparently close to the minimum value. Such low K mass fractions were already found in Crop 1 on Soils 12, 13, 17 and 19, indicating K deficiency right from the beginning. Crop 2 had low K mass fractions on the same soils and on Soil 18, where values went down to 2 g kg^{-1}, which is extremely low (Nijhof, 1987). Rice plants almost stopped growing, although they still extracted some K in Crop 3. The uptake of K was very low on the loamy to sandy soils 17, 18, 19. In Crop 3, K mass fractions were still above 5 g kg^{-1} on Soils 2, 4 and 8, suggesting that soil K was not yet completely exhausted.

Fig. 3.2 shows the relation between crop dry matter and mass fraction of plant K for Crops 1, 2 and 3. According to this graph, K mass fraction for Crop 1 was mostly below 11 g kg^{-1}. Dobermann et al. (1998) suggested that the critical K level at tillering stage in the upper most expanded leaf (Y leaf) is 10-15 g kg^{-1}, on the basis of reports by Yoshida (1981), De Datta and Mikkelsen (1985) and Rao and Sekhon (1988). The conclusion is that, even in the first crop, many soils had already a too low supply of K to plants, and in the second and third crop, plants were clearly deficient in K in all soils.

Fig. 3.3 shows the cumulative dry-matter production and K uptake on Soils 2, 6 and 11, which are representative for soils of Groups 1, 2 and 3, respectively, (see below in Section 3.3.2.2). The decrease in uptake was stronger than that in dry-matter

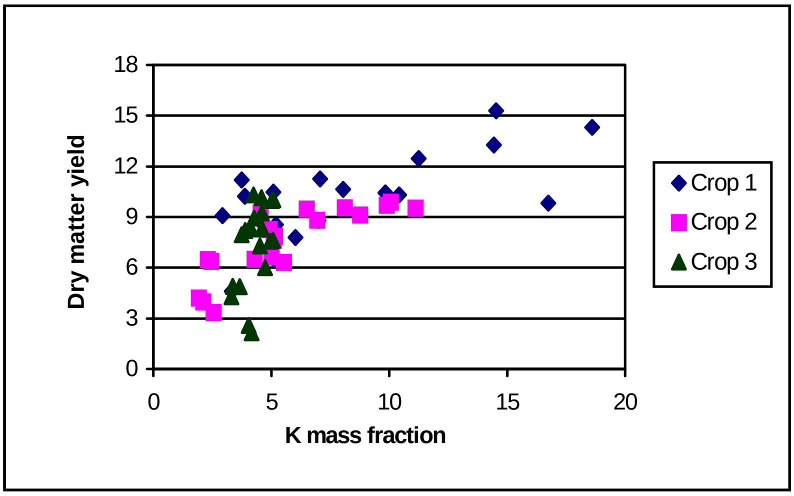


Figure 3.2: Relations between crop dry-matter production (g kg^{-1} soil) and K mass fraction (g kg^{-1}) of the successive crops.

yield, when going from Crop 1 to Crop 3, indicating that the decrease in soil K supply affected K uptake more than dry matter yield.

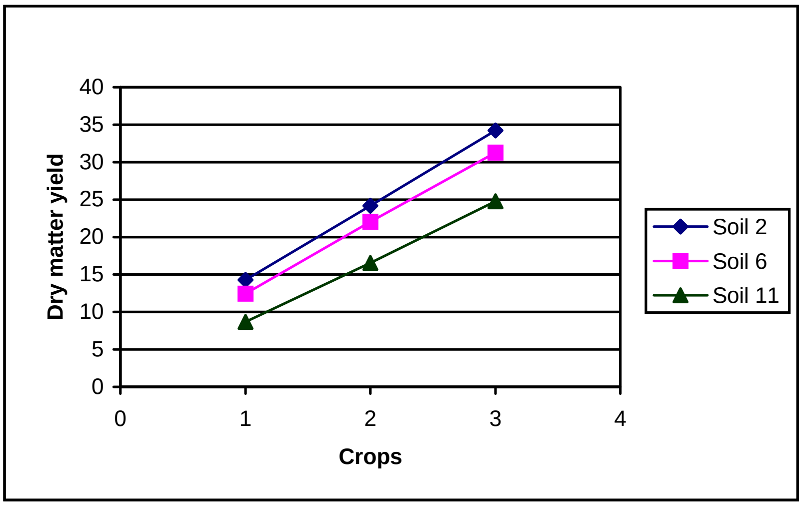
3.3.2 Laboratory studies

3.3.2.1.Preliminary study on extractions with NaTPB

Table 3.6 presents the amounts of K that were extracted with the various NaTPB procedures. The amounts of K extracted with 0.2 M NaTPB were about twice the amounts extracted with 0.067 M NaTPB. The amounts of K extracted at 1, 5 and 15 minutes increased and were roughly in the proportion 0.75:1:1.5. It is to be expected that with higher concentrations of NaTPB and longer extraction periods still more K is extracted from soil.

3.3.2.2.Main study on K fractionation

The results of the fractionation of soil K at the beginning and the end of the exhaustion greenhouse experiment are shown in Table 3.7. The amounts of K extracted differed widely between soils. This reflects the different characteristics of the soils such as texture, type of minerals in the clay and silt fractions, and other factors such as saline water intrusion and previous K management.



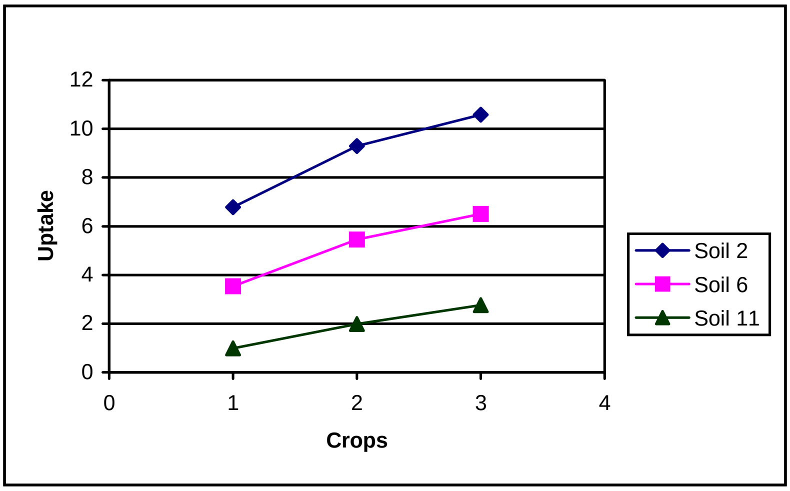


Fig 3.3: Cumulative dry-matter production (g kg^{-1} soil) (top) and K uptake (mmol kg^{-1} soil) (bottom) by 1, 2 and 3 crops on some selected soils.

Table 3.6. Amounts of K (mmol kg^{-1}) extracted by NaTPB as a function of concentrations (M) and extraction times (minutes) in five soils.

Concentration (M)		0.067 M			0.2 M	
Time (min)		1	5	15	1	5
Soil	Site					
2	Tan An	5.58	9.87	11.28	11.85	20.04
6	Chau Phu	3.78	5.72	8.52	7.92	13.8
9	CLRRI-NP	2.42	3.01	6.13	5.32	9.51
12	Binh Phu	1.91	2.14	2.7	3.87	5.85
17	Cau Ke	1.56	1.76	2.65	3.53	4.18

At the beginning, K($CaCl_2$) was about 33% of K(NH_4OAC) (Figure 3.4). K(NH_4OAC) was about 16% of K(NaTPB) (Fig 3.5), but this relationship was rather weak. Three groups of soil could be distinguished here. Points located near the regression line (Group 2) could be soils in which exchangeable and non-exchangeable K are more or less in equilibrium. The corresponding soils are 5, 6, 7, 8, 9, 12, 13, 17, 18 and 19, and their average ratio of K(NH_4OAC) to K(NaTPB was 0.19. The cluster above the regression line (Group1) comprises Soils 1-4 with relatively high ratios of exchangeable K to non-exchangeable K (on average 0.22). These soils are often saline-intruded and rice straw is frequently burned, resulting in ‘high’ labile K. The cluster below the regression line (Group3) consists of Thoai Son, Vinh Trinh (10, 11), and three Tan Chau soils (14-16). Thoai Son soil is low in exchangeable K, probably because this soil is affected by acid conditions (of the surrounding area). Vinh Trinh and the 3 Tan Chau soils are silty clay loam soils, which often have low exchangeable K, but high non-exchangeable K because of low CEC and high content of mica in the silt fraction (Uehara, 1974). They have relatively low labile K, and their average ratio of K(NH_4OAC) to K(NaTPB) was 0.08. These soils may behave differently in supplying K to a crop as shown by the slope of the regression line between K(NH_4OAC) and K(NaTPB) at the beginning and at the end (Fig. 3.5). Soils of Group 1 are relatively low and soils of Group 3 are relatively high in K(NH_4OAC) at the end of the greenhouse experiment. The average ratio

Table 3.7. Soil K fractions (mmol kg^{-1}) as measured by different extraction methods. Upper half: at the beginning of the greenhouse experiment; lower half: at the end of the greenhouse experiment.

Soil	Site	$CaCl_2$, 0.01 M	NH_4OAc, 1 M	NaTPB, 0.2 M	HNO_3, 1 M	HNO_3, 3 M	$HClO_4$-HF	NH_4OAc/ NaTPB
		At the beginning						
1	Cang Long -TV	1.56	4.34	16.14	11.09	10.72	498	0.27
2.	Tan An - LA	1.32	4.03	20.04	12.03	11.70	462	0.20
3.	Cho Moi - AG	1.66	3.64	17.59	11.62	13.06	588	0.21
4.	Chau Thanh - KG	1.02	3.42	18.52	8.13	7.42	365	0.18
5.	Cai Lay - TG	0.59	2.69	15.66	10.83	11.21	477	0.17
6.	Chau Phu - AG	0.62	1.84	13.80	9.06	10.59	556	0.13
7.	CLRRI- NP plot	0.35	1.55	9.51	4.73	4.84	429	0.16
8.	2 CLRRI – NPK plot	0.45	1.74	9.77	5.01	5.38	454	0.18
9.	2 CLRRI – NP plot	0.40	1.69	8.65	5.04	5.91	434	0.20
10.	Thoai Son - AG	0.36	1.39	13.34	5.51	6.04	461	0.10
11.	Vinh Trinh -TN-CT	0.50	1.22	12.20	6.56	7.43	498	0.10
12.	Binh Phu -MH - LA	0.20	1.28	5.85	4.41	3.80	237	0.22
13.	Vinh Hung-MH-LA	0.15	1.00	4.86	2.40	4.85	353	0.21
14.	Tan Chau (Trang)	0.41	1.06	12.54	9.46	9.33	547	0.08
15.	Tan Chau (Bon)	0.30	1.03	14.96	10.65	10.25	560	0.07
16.	Tan Chau (Tho)	0.28	0.85	12.70	8.55	8.63	507	0.07
17.	Cau Ke - TV	0.48	0.89	4.18	3.89	4.61	300	0.21
18.	An Cu - AG	0.55	0.71	2.59	3.73	2.84	225	0.27
19.	Go Tranh-MH-LA	0.24	0.52	2.82	0.31	0.47	69	0.18

Soil	Site	$CaCl_2$, 0.01 M	NH_4OAc, 1 M	NaTPB, 0.2 M	HNO_3, 1 M	HNO_3, 3 M	$HClO_4$-HF	NH_4OAc/ NaTPB
		At the end						
1.	Cang Long -TV	0.51	1.72	10.56	7.48	8.28	nd [a/]	0.16
2.	Tan An - LA	0.33	1.91	14.17	7.83	11.06	nd	0.13
3.	Cho Moi - AG	0.21	1.09	9.68	8.38	10.45	nd	0.11
4.	Chau Thanh - KG	0.27	1.64	11.42	5.45	8.60	nd	0.14
5.	Cai Lay - TG	0.26	1.29	9.49	8.21	10.94	nd	0.16
6.	Chau Phu - AG	0.23	1.05	9.09	7.69	8.95	nd	0.12
7.	CLRRI- NP plot	0.28	1.40	6.17	4.80	6.28	nd	0.23
8.	2 CLRRI – NPK plot	0.33	1.57	7.93	5.36	7.17	nd	0.20
9.	2 CLRRI – NP plot	0.28	1.25	6.60	3.88	5.61	nd	0.19
10.	Thoai Son - AG	0.24	1.13	11.48	4.23	7.19	nd	0.10
11.	Vinh Trinh -TN-CT	0.39	0.76	10.64	6.04	8.17	nd	0.07
12.	Binh Phu -MH - LA	0.13	0.85	3.20	1.46	2.78	nd	0.26
13.	Vinh Hung-MH-LA	0.11	0.88	3.33	1.27	2.81	nd	0.26
14.	Tan Chau (Trang)	0.29	1.11	9.84	7.96	11.04	nd	0.11
15.	Tan Chau (Bon)	0.34	1.24	12.73	8.79	12.17	nd	0.10
16.	Tan Chau (Tho)	0.33	1.17	10.92	7.70	10.77	nd	0.11
17.	Cau Ke - TV	0.23	0.81	3.06	2.52	3.46	nd	0.27
18.	An Cu - AG	0.11	0.31	2.06	3.41	2.06	nd	0.15
19.	Go Tranh-MH-LA	0.15	0.38	2.26	0.05	0.05	nd	0.17

[a/] nd : not determined

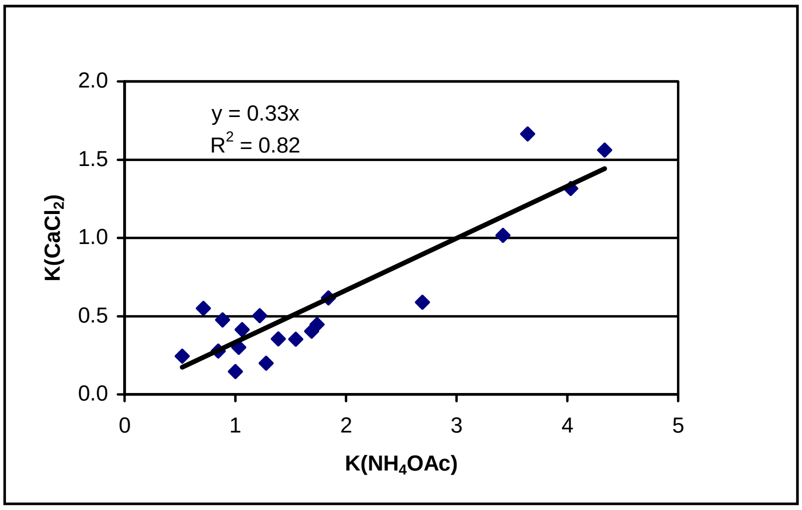


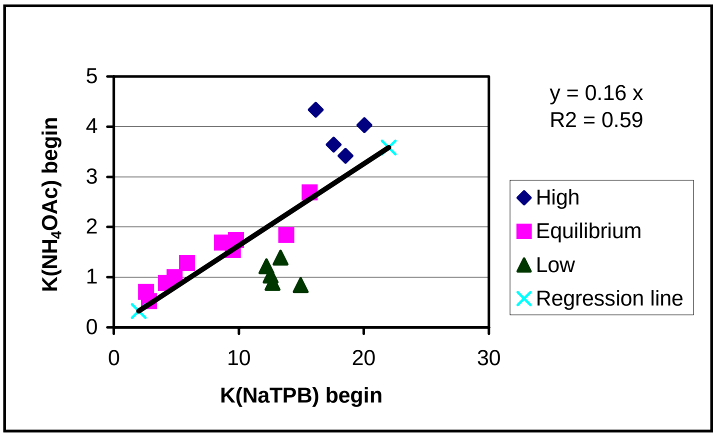
Fig 3.4: Relation between K($CaCl_2$) and K(NH_4OAc) expressed in mmol kg^{-1} at the beginning of the exhaustion experiment.

K(NH_4OAC) to K(NaTPB) changed from 0.22, 0.19 and 0.08 at the beginning to 0.14, 0.20 and 0.10 at the end, for Groups 1, 2 and 3, respectively. This suggests that Group 1 released much exchangeable K during the experiment, and Groups 2 and 3 little.

3.3.3. Relations between K uptake by the crop and soil K fractions

3.3.3.1.Preliminary study on extraction with NaTPB

Table 3.8 shows that all five tested procedures for NaTPB gave good relations with K uptake by 1, 2 and 3 crops. The best results were with the uptake by 2 crops. Regression coefficients higher than 1 indicate that plants took up more K than was extracted by the particular method. Such extraction methods were considered to be mild. The slopes of the regression lines or regression coefficients decreased with increasing extraction times and increasing concentration of NaTPB, because the amounts of extracted soil K increased (as was shown in Table 3.6), which is in agreement with the results found by Cox et al. (1999). For three crops, the regression coefficients were less than 1 only in the cases of 0.067 M and 15 minutes extraction



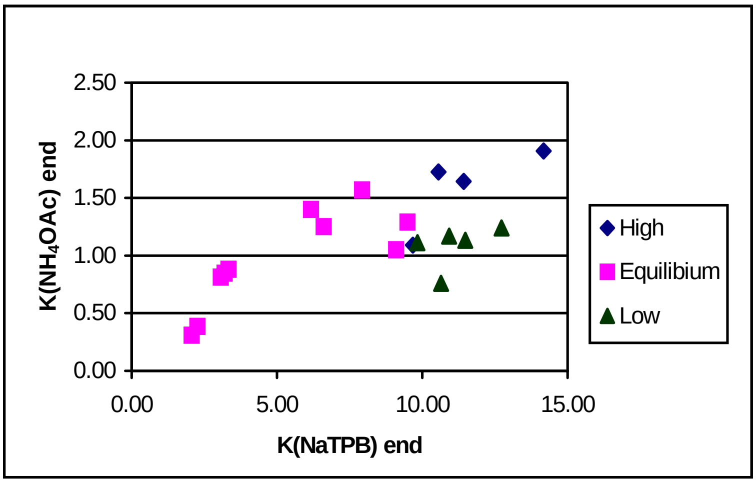


Figure 3.5 : Relations beteen K(NH4OAc) and K(NaTPB) expressed in mmol kg^{-1} at the beginning (top) and at the end (bottom) of the exhaustion experiment. Soil are grouped according to the position with regard to the regression line of the relation of K(NH4OAc) and K(NaTPB) at the beginning.

and of 0.2 M NaTPB and 1 and 5 minutes extractions. Uptake of K by 3 crops was estimated as 84%, 83%, and 49% of K extracted by these methods, if the regression lines were forced through the origins (Table 3.8). As the R^2 value for 0.2 M NaTPB and 5 minutes extraction was a little better than the one for 0.067 M and 15 minutes extraction, it was decided to use 0.2 M NaTPB and 5 minutes extraction time in the

Table 3.8. Values of regression coefficients (a,b), intercepts (I), and R^2 of equations relating K uptake by 1, 2 and 3 crops, respectively, to soil K, as extracted with 0.067 M NaTPB in 1, 5 and 15 minutes, and with 0.2M NaTPB in 1 and 5 minutes. Two types of equations are used: $Y = a * X$ and $Y = b * X + I$. Also the minimum values of soil K required before any K uptake takes place (MIN) are given; they were calculated as: MIN= - I/b.

Crops	Molarity (M)	Time	a	R^2	b	I	R^2	MIN
1	0.067	1	1.06	0.89	1.43	-1.36	0.97	0.95
		5	0.67	0.97	0.70	-0.14	0.97	0.20
		15	0.51	0.90	0.62	-0.87	0.94	1.40
	0.2	1	0.50	0.90	0.68	-1.45	0.98	2.13
		5	0.30	0.93	0.37	-0.92	0.97	2.49
1+2	0.067	1	1.50	0.91	1.99	-1.86	0.98	0.93
		5	0.95	0.97	0.97	-0.14	0.97	0.14
		15	0.72	0.93	0.87	-1.23	0.97	1.41
	0.2	1	0.71	0.91	0.95	-1.98	0.99	2.08
		5	0.42	0.95	0.51	-1.27	0.99	2.49
1+2+3	0.067	1	1.76	0.92	2.21	-1.71	0.97	0.77
		5	1.10	0.96	1.07	0.21	0.96	-0.20
		15	0.84	0.96	0.97	-1.07	0.98	1.10
	0.2	1	0.83	0.93	1.06	-1.85	0.98	1.75
		5	0.49	0.96	0.57	-1.08	0.99	1.89

fractionation study. Cox et al.(1999) also adopted this procedure, partly because 5 min extraction was more convenient than a shorter period.

Adaptability to routine soil testing is another consideration in selecting a method. Because NaTPB is an expensive chemical, high concentration of NaTPB means high costs for routine work, and therefore NaTPB solution with lower concentration like 0.067 M NaTPB combined with a 15 min extraction time can also be a candidate for non-exchangeable but plant-available K in routine soil analysis.

3.3.3.2.Main study on K fractionation

Fig. 3.6 shows the relations between dry-matter yield of 1, 2 and 3 crops and initial K(NH_4OAc) and K(NaTPB), respectively (initial K, measured before the start of the experiment). In general, the relation was clearer for K (NH_4OAC) than for K(NaTPB).

Critical soil K values, at critical K mass fraction of 10 to 15 g kg^{-1}, ranged from 2.1 to 3.2 mmol kg^{-1} for K(NH_4OAC), and from 11.5 to 17.3 mmol kg^{-1} for K(NaTPB (Fig. 3.7).

The relations between crop K uptake (K uptake was corrected for K in seed for each crop) and soil K fractions were linear (Fig.3.8). The values of the regression coefficients (a), intercepts (I), and R^2 of the linear equations relating K uptake to soil K, are shown in Table 3.9 for Soils 2-18, and in Table 3.10 for the clay soils only (Soils 2-10 and soils 12-13). The minimum values of soil K required before any K uptake takes place (MIN) are also given. In each case, the order of the soil extraction methods was (from weak to strong): 0.01 M $CaCl_2$, 1 M NH_4OAc pH 7, 1 M HNO_3, 3 M HNO_3, 0.2 M NaTPB (5 min), and $HClO_4$-HF.

All regression coefficients increased from 1 to 2 to 3 crops, which was obviously the result of the cumulative uptake by three crops. All regression coefficients decreased in the order $CaCl_2$, NH_4OAC, 1 M HNO_3, 3 M HNO_3, NaTPB and $HClO_4$-HF confirming that this is indeed the order of increasing extracting power. The differences between 1 M HNO_3 and 3 M HNO_3 were small, indicating that there was little increase in K dissolution with increasing acid concentration. Total K (determined with $HCLO_4$-HF) was weakly related to crop uptake. The relation improved when only clay soils were considered and when the number of crops increased.

The values for minimum K increased in the order $CaCl_2$, NH_4OAc, 1 M HNO_3, 3 M HNO_3, NaTPB and $HCLO_4$-HF, again indicating that this is an order of increasing extracting power. The differences between 1 M HNO_3 and 3 M HNO_3 were much smaller than the differences with the other solutions. Therefore, the extraction with 3 M HNO_3 was not examined further. The minimum values estimated for clay

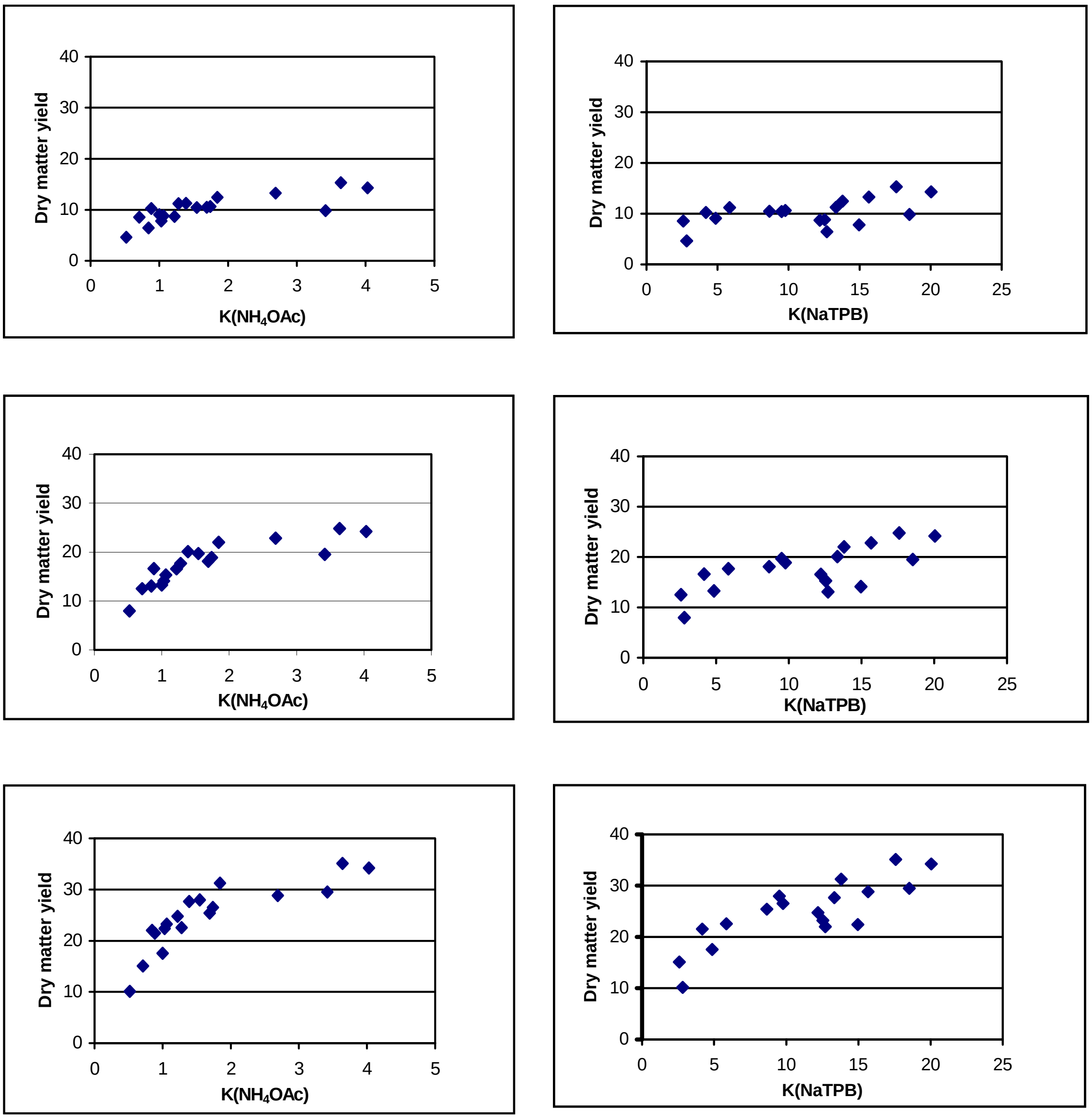
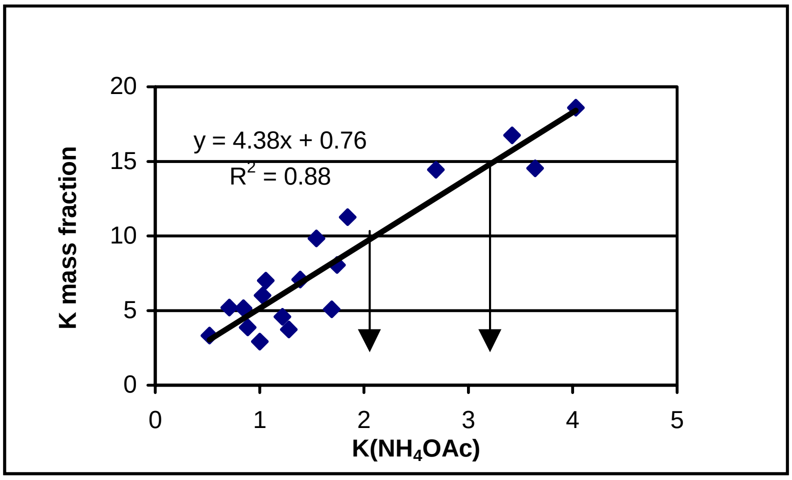


Figure 3.6: Relations between dry-matter yield of 1 (top), 2 (middle) and 3 (bottom) crops (mg kg^{-1}soil) and soil K (mmol kg^{-1}) at the beginning of the exhaustion experiment, measured with 1 M NH_4OAc (left) and 0.2 M NaTPB (right).

soils in Crop 1 are -0.22, 0.43, 1.72, 1.89, and 3.75 mmol kg^{-1} for 0.01 M $CaCl_2$, 1 M NH_4OAc, 1 M HNO_3, 3 M HNO_3, and 0.2 M NaTPB, respectively (Table 3.10). For K(NH_4OAC), the minimum K is the value below which any K uptake was from the non-exchangeable pool.



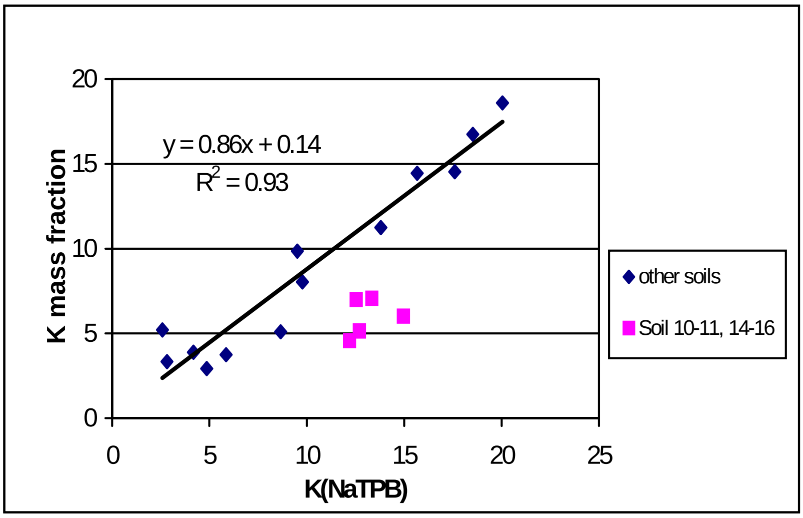


Figure 3.7: Derivation of crititial level of K(NH_4OAc) (mmol kg^{-1}) (top) and K(NaTPB) (mmol kg^{-1}) (bottom) for critical K mass fractions set at 10 and 15 g kg^{-1}.

Going from 1 crop via 2 crops to 3 crops, the R^2 values decreased for $CaCl_2$, remained about the same and highest for NH_4OAc, and increased for the stronger extracting solutions of 1 M HNO_3, 3 M HNO_3, NaTPB and $HClO_4$-HF when all soils were considered (Table 3.9). This suggests that K($CaCl_2$) could indicate K availability

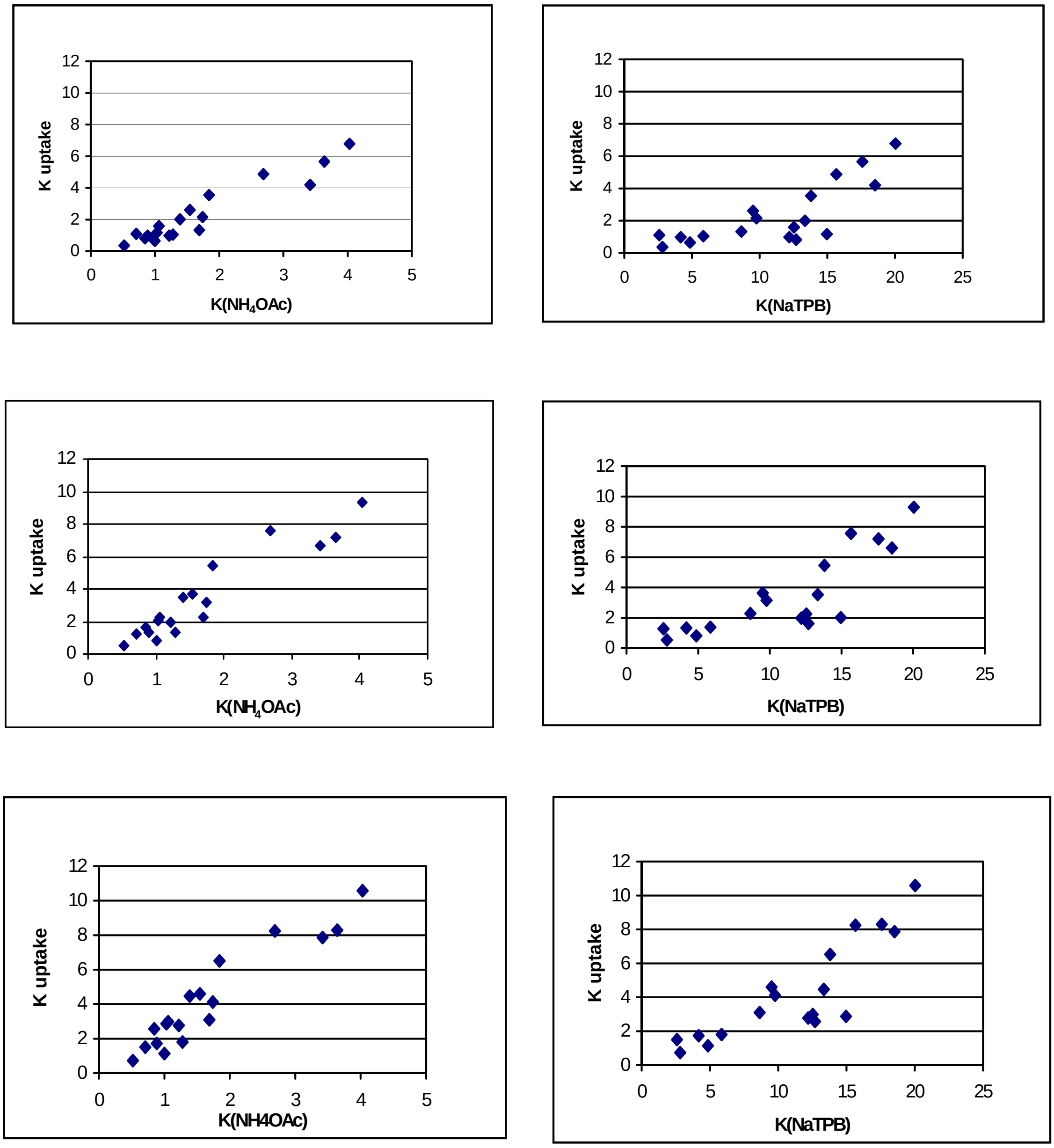


Figure 3.8: Relations between K uptake by 1 (top), 2 (middle) and 3 (bottom) crops (mmol kg^{-1} soil) and soil K (mmol kg^{-1}) as measured with 1 M NH_4OAc_3 (left) and 0.2 M NaTPB (right) at the beginning of the exhaustion expreriment.

for the first crop only. For the next crops, plants relied on K forms other than those extracted by $CaCl_2$. In general, R^2 values were higher for the clay soils than for all soils; an exception is R^2 for K(NH_4OAc), which were lower for clay soils than for all soils. Also the minimum K requirements (MIN) were higher for clay soils than for the other soils.

Table 3.9. Values of regression coefficients (a,b), intercepts (I), and R^2 of equations relating K uptake by 1, 2 and 3 crops, respectively, to soil K, as extracted with different extracting solutions (Soils 2-19). Two types of equations are used: Y= a * X and Y = b * X + I. Also the minimum values of soil K required before any K uptake takes place (MIN) are given; they were calculated as: MIN= - I/b. Uptake and soil K are both expressed in mmol per kg of soil.

Crops	Solution	a	R^2	b	I	R^2	MIN
1	$CaCl_2$	4.19	0.73	4.09	0.08	0.74	-0.02
	NH_4OAc	1.46	0.88	1.72	-0.60	0.91	0.35
	1 M HNO_3	0.35	0.51	0.40	-0.41	0.52	1.02
	3 M HNO_3	0.34	0.50	0.40	-0.51	0.51	1.28
	0.2 M NaTPB	0.22	0.58	0.27	-0.71	0.60	2.6
	$HClO_4$-HF	0.005	0.06	0.004	0.041	0.07	-10.3
1+2	$CaCl_2$	5.98	0.64	5.36	0.50	0.66	-0.09
	NH_4OAc	2.12	0.88	2.38	-0.59	0.90	0.25
	1 M HNO_3	0.52	0.54	0.58	-0.46	0.55	0.79
	3 M HNO_3	0.50	0.52	0.56	-0.58	0.53	1.03
	0.2 M NaTPB	0.33	0.65	0.40	-1.03	0.68	2.55
	$HClO_4$-HF	0.008	0.21	0.009	-0.23	0.21	25.6
1+2+3	$CaCl_2$	7.08	0.61	5.86	1.00	0.65	-0.17
	NH_4OAc	2.52	0.89	2.61	-0.21	0.90	0.08
	1 M HNO_3	0.63	0.57	0.65	-0.17	0.58	0.26
	3 M HNO_3	0.60	0.56	0.63	-0.31	0.56	0.49
	0.2 M NaTPB	0.39	0.71	0.46	-0.87	0.73	1.91

The R^2 values for clay soils were highest for 1 M HNO_3 and NaTPB, rather high for K(NH_4OAc) and low for K($CaCl_2$). Also the minimum K requirements (MIN) were higher for clay soils than for the other soils. The regression coefficients of the line through the origin were larger than 1 for K($CaCl_2$) and K(NH_4OAc), indicating that more K was taken up than could be extracted with these methods. Therefore K($CaCl_2$) and K(NH_4OAC) could not explain the amounts of K that were

Table 3.10: Values of regression coefficients (a,b), intercepts (I), and R^2 of equations relating K uptake by 1, 2 and 3 crops, respectively, to soil K, as extracted with different extracting solutions. Clay soils only (Soils 2-10 and 12-13). Two types of equations are used: Y= a * X and Y = b * X + I. Also the minimum values of soil K required before any K uptake takes place (MIN) are given; they were calculated as: MIN= - I/b. Uptake and soil K are both expressed in mmol per kg of soil.

Crops	Solution	a	R^2	b	I	R^2	MIN
1	$CaCl_2$	4.49	0.72	3.67	0.80	0.78	-0.22
	NH_4OAc	1.50	0.85	1.78	-0.77	0.88	0.43
	1 M HNO_3	0.47	0.88	0.58	-1.00	0.92	1.72
	3 M HNO_3	0.43	0.76	0.55	-1.04	0.80	1.89
	0.2 M NaTPB	0.27	0.79	0.36	-1.35	0.86	3.75
	$HClO_4$-HF	0.007	0.28	0.012	-2.10	0.33	175
1+2	$CaCl_2$	6.35	0.57	4.74	1.57	0.69	-0.33
	NH_4OAc	2.15	0.83	2.41	-0.68	0.84	0.28
	1 M HNO_3	0.67	0.89	0.82	-1.11	0.92	1.35
	3 M HNO_3	0.62	0.75	0.74	-1.09	0.78	1.47
	0.2 M NaTPB	0.39	0.85	0.51	-1.80	0.92	3.53
	$HClO_4$-HF	0.011	0.28	0.016	-2.54	0.32	159
1+2+3	$CaCl_2$	7.41	0.51	5.20	2.16	0.70	-0.42
	NH_4OAc	2.52	0.85	2.62	-0.26	0.85	0.10
	1 M HNO_3	0.79	0.89	0.86	-0.66	0.90	0.77
	3 M HNO_3	0.73	0.75	0.79	-0.60	0.76	0.76
	0.2 M NaTPB	0.46	0.90	0.56	-1.54	0.94	2.75
	$HClO_4$-HF	0.013	0.31	0.018	-2.46	0.34	137

taken up, and there must have been a considerable supply of K from non-exchangeable forms.

Because the relation between crop uptake and K($CaCl_2$) was rather poor, it is suggested to use K(NH_4OAc), which extracts both soluble K and exchangeable K, as indicator for the first pool in a three-pools model. The increase of R^2 for the relation between crop uptake and K(NaTPB) with successive crops suggests that K(NaTPB) can be used to describe the first 2 pools of K in the model. For the clay soils, also K (1M HNO_3) showed a good relation to crop uptake but not as good as K(NaTPB). In

Fig. 3.9 the uptake by 3 crops is plotted against the decrease in K(NaTPB) and K(HNO_3) between the beginning and the end of the experiments. Also this relation is better for K(NaTPB) than for K(HNO_3). Therefore, K(NaTPB) is suggested to be the better extractant to determine the sum of Pool 1 and Pool 2 in a three-pools model.

The regression equations for NaTPB in Tables 3.9 and 3.10 are rewritten for the subsequent crops as follows:

K uptake (1)=0.27*[K(NaTPB)-2.60]

K uptake (1+2) = 0.40 *[K(NaTPB) – 2.55]

K uptake (1+2+3)= 0.46*[K(NaTPB)-1.91]

For clay soils, the equations are as follows:

K uptake (1)=0.36*[K(NaTPB)-3.76]

K uptake (1+2) = 0.51 *[K(NaTPB) – 3.50]

K uptake (1+2+3)= 0.56*[K(NaTPB)-2.73]

These linear regression equations suggest that K(NaTPB) consists of two parts: the constant (intercept) reflects the part that was unavailable during the considered period, and the regression coefficient reflects the fraction of the available part that was taken up during the growing period. Evidently, the longer the growing period (the more crops are grown), the smaller the unavailable part is and the higher the fraction taken up of the available part of K.

The fraction taken up from K(NaTPB) was higher in clay soils than in all soils. This can be explained by the high illite content in most of recent alluvial soils (Chapter 1). Cox et al (1999) found a contribution to crop uptake of 16-70% of non-exchangeable K. Mengel (1993) also showed that soils rich in illite have a large reserve of non-exchangeable but plant-available K.

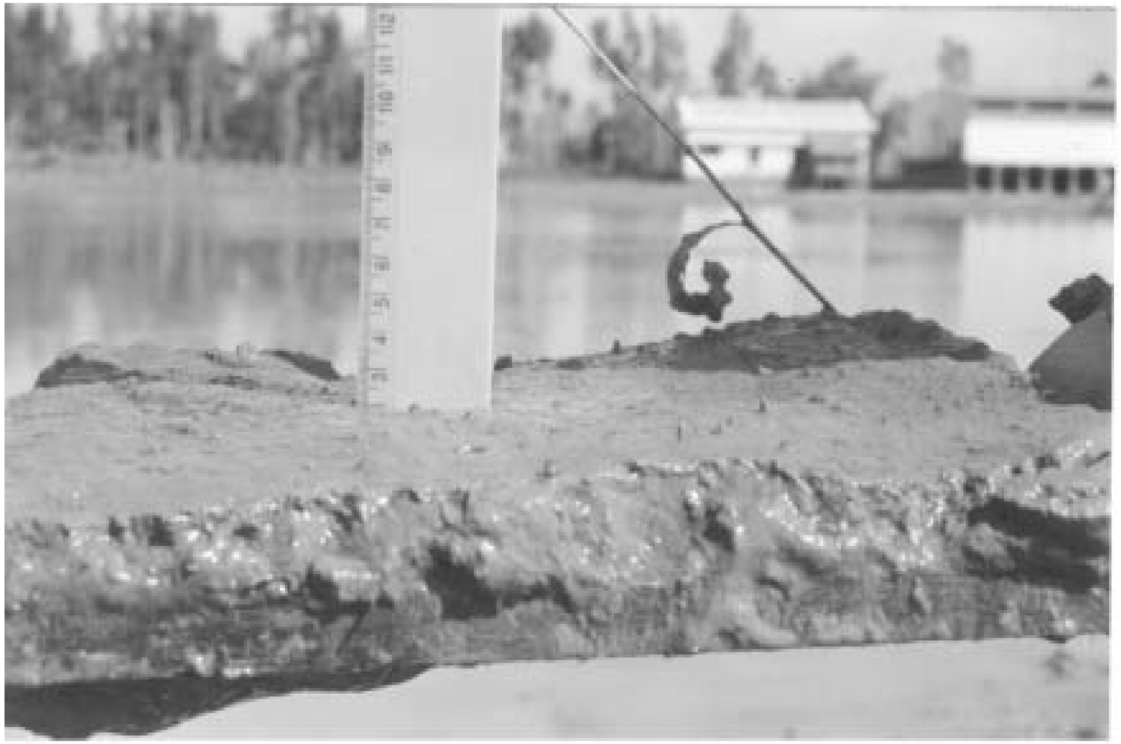
3.4. Conclusions

The experiments described in this section had the following objectives: (i) to find the NaTPB extraction procedure that was best related to K uptake by to plants, (ii) to investigate the potential and the reliability of the K extractions by 0.01 M $CaCl_2$, 1 M NH_4OAC pH 7, 1 and 3 M HNO_3, the selected NaTPB procedure, and $HClO_4$-HF (Total K) for the characterisation of the pools in a three-pools model. The following answers were obtained.

Among the tested procedures of K extraction with NaTPB, the procedure with 0.2 M NaTPB and 5 minutes extraction showed the highest correlation with crop uptake and is therefore recommended. For routine analyses, the procedure 0.067 M NaTPB and 15 minutes extraction is an acceptable cost-effective alternative.

The order of increasing K extracting power of the tested solutions was: 0.01 M $CaCl_2$ < 1 M NH_4OAc pH 7 < 1M HNO_3 < 0.2 M NaTPB 5 min < $HClO_4$-HF, confirming the expectations.

The crop uptake showed best correlation with K(NH_4OAc) and K(NaTPB). It is suggested to use K(NH_4OAc) as the first or labile pool in a three-pools model, K(NaTPB) as the sum of the first and second (or intermediate) pools, and the difference between K(total) and K(NaTPB) as the third or stable pool.



Sampling and measuring of sediment deposition in the field in An Phong- Dong Thap.

CHAPTER 4

KINETICS OF POTASSIUM ADSORPTION-DESORPTION AND FASTENING -REMOVAL IN SOME RICE SOILS IN THE MEKONG DELTA

4.1. Introduction

The supply of K by soils to plants is a dynamic, complex process involving transformations between different K pools. Selim et al. (1976) considered a series of four K pools in soil, and described the dynamic reactions between solution, exchangeable, non-exchangeable and mineral K in forward direction as *adsorption, fixation, immobilization* and in backward reaction as *weathering, release and desorption* (Fig 4.1a). The model of Selim et al. (1976) has been helpful in increasing the understanding of the K dynamics in soils, but experimental verification of the various pools and rate coefficients of this model is complex and has not been done yet.

Many studies have been conducted to characterize specific pools and rate coefficients such as for adsorption-desorption and fixation-release kinetics. Methods used to determine the pools and rate coefficients experimentally include batch (Sharpley, 1987; Rao et al, 1999) and miscible displacement techniques (Sparks et al., 1980), while electro-ultrafiltration (Ziadi et al., 2001), H^+-resin (Martine and Sparks, 1983), Ca^{2+}-resin (Goulding, 1984), and NaTPB have been used as a sink for K (Cox and Joern, 1997). The kinetic relations have been described by different equations including first order, parabolic, Elovich, and power equations (Mum et al., 1976; Sparks et al., 1980; Martin and Sparks, 1983; Dhillon et al., 1989; Hundal and Pasricha, 1993; López-Piñeiro and Navarro, 1997; Rao et al, 1999; Ziadi et al., 2001). Hundal and Pasricha (1993) found two simultaneous first order equations for the release of non-exchangeable K representing a rapid and a slow reaction. They attributed the presence of two simultaneous first order reactions to the mineralogy of the clay fraction of the soils. The slow release of K was due to the ‘specific fixation sites’ of the vermiculite in the soils studied. Rao et al. (1999) also found two phases of K release. A high release rate constant was found for the first period from 0 to 73 h and a lower rate constant for the overall period from 0 to 217 h. They explained that the fast rate of K release was from easily accessible sites on the external planar surface and the slow release is from the interlayer sites of the clay component. Goulding (1984) found four slopes of K release using Ca-resin as a sink and reported that the total K release versus $t^{1/2}$ appeared to be comprised of four linear parts.

According to Mc Lean and Watson (1985), there are 4 types of bonds of K held in the interlayer of micaceous clay. The first type is the K-specific bond in wedge-shaped voids of the micaceous clays, which has the first priority in K fixation to the interlayer spaces. When some of these voids are closed, the second type of bond relates to voids remaining open. The third type of bond refers to permanent charge sites on the exposed internal surfaces of the micas and the fourth to the external surface. The pH-dependent charge is another site for adsorption of basic cations including K^+. Because of the preference for H^+ ions, these sites also have major effects on mobilization of the basic cations being hydrolyzed or otherwise replaced by H^+ ions from other sources. The greater the portion of K present at the sites with high preference, the more difficult it is to release K. Evidently, soils are poly-functional ion exchangers formed by a mixture of organic matter and soil particles with different mineralogy. Their retention sites are multiple and hence the rate of K release is not a constant, but changes over time.

So far, results suggest that solution K, exchangeable K, non-exchangeable K and mineral K (e.g. Fig 4.1a) determine the soil K supply in short and medium-long terms. In this study, exchangeable K (but including solution K) was assumed to be K(NH_4OAc), and this pool is called labile K (LK). Non-exchangeable K was determined by K(NaTPB) which includes K(NH_4OAc). Net K(NaTPB) calculated as the difference between K(NaTPB) and K(NH_4OAc) is called intermediate K (IK). The backward reaction between K(NH_4OAc) and soil solution (or external solution) was defined as *desorption* and the reverse reaction as *adsorption* (Fig 4.1b). The transformation of K from K(NaTPB) to solution was defined as *removal* and the reverse reaction from solution to K(NaTPB) as *fastening* (Fig 4.1c).

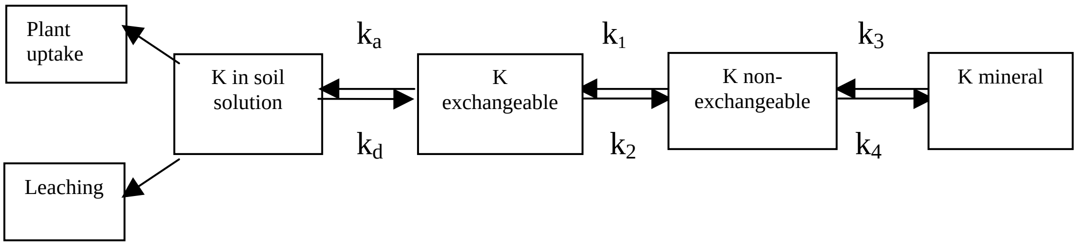


Figure 4.1a: Kinetic reactions between soil K pools. The rate coefficients refer to adsorption (k_a), desorption (k_d), fixation (k_1), release (k_2); immobilization (k_3) and weathering (k_4). (Selim et al., 1976).

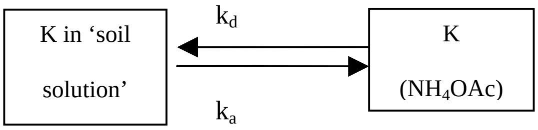


Figure 4.1b: Kinetic reactions between K(NH_4OAc) and 'soil solution' (or external solution. The rate coefficients refer to adsorption (k_a), and desorption (k_d) in this study (see text).

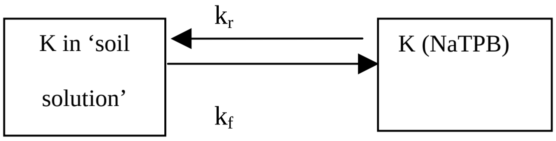


Figure 4.1c: Kinetics reaction between K(NaTPB) and soil solution (or external solution). The rate coefficients refer to removal (k_r), and fastening (k_f) in this study.

The general objective of the study described here was to find a uniform equation to describe the release of K(NH_4OAc) and K(NaTPB) to soil solution (or external solution). For that purpose, a first order equation similar to the equation found for carbon mineralization by Yang and Janssen (2002) in which the rate coefficient is allowed to change over time was tested. The specific objectives were: (i) to determine rate coefficients of K adsorption-desorption and fastening-removal kinetics, (ii) to validate first order equations for K adsorption-desorption and fastening-removal kinetics, and (iii) to test the usefulness of the Yang and Janssen equation to describe K removal from non-exchangeable K for some soils in the Mekong Delta.

4.2. Materials and Methods

4.2.1. Soils used in the study

A sediment sample from Thoi Thanh-O Mon collected during the flood in 2000, and seven representative soils (Soils 1, 2, 6, 7, 10, 12 and 17) described in Chapter 3 were used in the study. Soils 1 (Cang Long), 2 (Tan An), 6 (Chau Phu), 7 (CLRRI-NP), and 10 (Thoai Son) are young alluvial illite-predominant clay soils with high to low K(NH_4OAc). Soil 12 (Binh Phu-Moc Hoa) is an old alluvial, kaolinite-predominant clay soil, and soil 17 (Cau Ke) is a loamy soil. Soil classification and physical and chemical properties of these soils were given in Chapter 3, and of the sediment in Chapter 2.

4.2.2. Potassium adsorption and fastening

4.2.2.1. Technical procedure

The method used for the assessment of K adsorption and fastening is similar to the miscible displacement method described by Sparks and Jardine (1981), but it was adjusted to the locally available equipment in Vietnam. The following steps were made:

- Moisture saturation: the soil (5 g) was put on to a plastic funnel using Whatman filter paper and saturated in 15 ml of 50 mg l^{-1} K solution (ratio of 1:3) in 15 minutes to make sure that all soil was homogeneously wet before the leaching started.

- Adsorption: the soil was leached with the 50 mg l^{-1} K solution supplied at steady rate to renew the 'soil solution' and to assess K adsorption at constant K concentration in the 'soil solution'. The solution was leached at a rate of about 1 ml per min for 15, 30, 60, 120, 240, 360, 720 and 1440 min.
- Washing and air-drying: after each time period of adsorption, soil in the filter was thoroughly rinsed with distilled water until no Cl was present in the leachate (test with $AgNO_3$) and then air-dried.
- K analysis: K held by the soil after each adsorption period was measured after extraction by 1 M NH_4OAc pH 7 for adsorbed K and after 5 minutes extraction with 0.2 M NaTPB for fastened K (see Chapter 3).

4.2.2.2. Mathematical procedure

It was assumed that rate of adsorption was linearly related to the "open" space for adsorption and fastening sites. For assessing K adsorption and fastening dynamics we used the following first order equation:

$$dK_t / dt = k (K_{max} - K_t)$$

or $$d(K_{max}-K_t)/(K_{max} - K_t) = - k\, dt \qquad \text{Eq. 4.1}$$

Rates of K adsorption and fastening were assumed to be related to K_{max}-K_t

where:

K_{max} = maximum amount of K that can be adsorbed or fastened (mmol kg^{-1})

K_t = K adsorbed or fastened at time t determined by 1 M NH_4OAc or 0.2 M NaTPB (mmol kg^{-1}), respectively.

k : rate coefficient (day^{-1});

The rate coefficient for adsorption [K(NH_4OAc)] calculated by Eq 4.1 is denoted as k_a, and the one for K fastening [K(NaTPB)] as k_f. K adsorbed will henceforth be indicated by K_L, where L stands for labile K and K fastened by K_{LI}, where L stands for labile, and I stands for intermediate K.

Integration of Eq. 4.1 yields:

$\ln (K_{max} - K_t) = -k\,t + \text{constant } C$

For t=0, K_t = K present at time zero (K_0)

therefore, constant $C = \ln (K_{max}-K_0)$

At time t:

$\ln (K_{max}-K_t) = -k\,t + \ln (K_{max}-K_0)$ Eq. 4.2

This equation has the linear form y= ax + b, where 'y'= $\ln (K_{max}-K_t)$, the regression coefficient 'a' is the rate coefficient (k) and intercept 'b'= $\ln(K_{max}-K_0)$. From the intercept and K_{max}, K_0 can be calculated.

Because an adsorption or fastening time of 1440 minutes as applied in the experiment, appeared a little too short to reach maximum adsorption and maximum fastening, it was necessary to estimate the values of K_{max}. This was done as follows:

- A parabolic equation was used for fitting K adsorption or fastening versus time; the first derivative was taken for determination of the maximum value from the equation. This was a first approximation of K_{max}. Some other estimates were 90, 110, 120%, or higher of the first estimate of K_{max}.

- Next $\ln (K_{max}-K_{L,t})$ was plotted versus time and the rate coefficient k was read from the slope of the line. This was done for the various estimates of K_{max}. For each soil, the equation which gave the best fit (highest R^2) was selected and the corresponding values of K_{max} and the rate coefficient k were considered as the final estimates.

This procedure is similar to the one applied by Stanford and Smith (1972) to assess nitrogen mineralization potentials. K_0 was estimated from the intercept of the line; the initial soil K value could not be used as some adsorption took place during moistening of soil samples with K solution before the official adsorption phase started.

4.2.3. Potassium desorption.

4.2.3.1 Technical procedure

Rate of K desorption was measured using duplicate samples of 5 g soil. The soil was put in a plastic funnel using Whatman filter paper and was moistened in 15 ml of 0.01 M $CaCl_2$ (ratio of 1:3) during 15 min. The soil samples were then leached with a 0.01 M $CaCl_2$ solution supplied at steady rate to renew the soil solution. The solution was leached out from the soil at a rate of about 1 ml per min during 15, 30, 60, 120, 240 and 360 min. After each time period of desorption, soil in the filter was thoroughly rinsed with deionized water until no Cl was present in the leachate (test with $AgNO_3$), and then air-dried. Residual K adsorbed by the soil after each leaching period was determined by 1 M NH_4OAc pH 7.

4.2.3.2. Mathematical procedure

It was assumed that the rate of desorption was proportional to the residual amount of labile K (K_L).

The first order equation applied for desorption of labile K (K_L) was as follows:

$$dK_L/dt = - k_d * K_{L,t}$$

$$dK_L/K_{L,t} = - k_d * dt \qquad \text{Eq 4 .3}$$

Integration equation 4.3 yields:

$$\ln K_L = -k_d t + C; \qquad \text{at } t = 0, \qquad C = \ln K_{L,0}$$

or $$\ln K_L = -k_d t + \ln K_{L,0} \qquad \text{Eq. 4.4}$$

where K_L = labile K adsorbed at time t; labile K was determined by K(NH_4OAc)

$K_{L,0}$ = labile K adsorbed at time t = 0 before the leaching starts

k_d = desorption rate coefficient

From the plot of ln K_L versus time, the desorption rate coefficient k_d was found as the slope of the regression line and K_0 from the intercept. Also here, the measured K_0 could not be used, because some desorption took place during the initial moistening with $CaCl_2$.

K(NH_4OAc) remaining in the soil at time t was calculated from:

$$K_{L,t} = K_{L,0} * \exp(-k_d\ t) \qquad \text{Eq. 4.5a}$$

Amount of K desorbed (K_{des}) at time t was calculated by:

$$K_{des} = K_{L,t} - K_{L,0} \qquad \text{Eq.4.5b}$$

4.2.4. Potassium removal

4.2.4.1. Technical procedure

K removal was determined using a NaTPB extraction procedure similar to that described by Cox et al. (1999), but at a NaTPB concentration of 0.067 M as used by Scott and Reed (1962). This concentration is lower than the one used for the analysis of fastened K (Section 4.2.2.1). For practical reasons, only five representative soil samples (Soil 2 (Tan An), 6 (Chau Phu), 7 (CLRRI-NP), 12 (Binh Phu) and 17 (Cau Ke), and a sediment sample from Thoi Thanh-O Mon were used (Section 4.2.1.). For each soil, a series of duplicate 0.5 g soil samples were incubated in 3 ml of 0.067 M NaTPB extracting solution for a period of 1, 15 and 30 min and for 1, 6, 12, 24, 96, 144 and 400 hours. At the end of each extraction period, precipitated K was recovered by 0.5 M NH_4Cl + 0.11 M $CuCl_2$ solution, and K in the extract was then measured by atomic absorption spectrophotometer, following the method described by Cox et al. (1999).

4.2.4.2. Mathematical procedure

Calculation of the rate coefficient for K removal (k_r), according to first order kinetics, was similar to the one for K desorption (k_d) (see Eq. 4.4), resulting in:

$$\ln K_{LI} = - k_r\ t + \ln K_{LI,0} \qquad \text{Eq. 4.6}$$

where

$K_{LI,0}$ = initial amount of labile and intermediate K in the soil at time t=0; it was assumed to equal the amount removed after 400 hours by 0.067 M NaTPB.

K_{LI} = labile and intermediate K remaining in the soil; it was calculated as the difference between $K_{LI,0}$ and K removed by 0.067M NaTPB at time t.

k_r = removal rate coefficient (day^{-1})

$K_{LI,t}$ at time t was calculated by

$$K_{LI,t} = K_{LI,0} * \exp(-k_r\ t) \qquad \text{Eq.4.7a}$$

Amount of K removed (K_{rem}) at time t was calculated by:

$$K_{rem} = K_{LI,t} – K_{LI,0} \qquad \text{Eq.4.7b}$$

As k_r was found to decrease with time, it was tried whether the Yang and Janssen (2002) method for first order reaction with a changing k rate could be applied. For that purpose, the average removal rate coefficient (k_{rav}) being the average rate between time 0 and time t was introduced; it was calculated as follows:

$$k_{rav} = 1/t\ (\ln K_{LI,0} – \ln K_{LI,t}) \qquad \text{Eq. 4.8}$$

where

$K_{LI,0}$ and $K_{LI,t}$ are as in Section 4.2.3.2.

Next ln k_{rav} was plotted versus ln time, and the linear regression line was calculated:

$$\ln (k_{rav})= -S^* \ln t + \ln R \qquad \text{Eq. 4.9a}$$

or $$k_{rav} = R^* t^{-S} \qquad \text{Eq 4.9b}$$

where

S = the regression coefficient, relating ln k_{rav} to ln t; S is dimensionless

ln R = intercept; dimension of R is t^{S-1}

From Equation 4.9, it follows that at t =1, R is k_{rav} between t=0 and t=1; it is the initial relative removal rate (k_{rav1}). The regression coefficient S is a measure of the rate at which k_{rav} decreases over time.

Substitution of Eq.4.9b in Eq.4.7a results in the following equation for calculation of $K_{LI,t}$:

$$K_{LI,t} = K_{LI,0} * \exp(-R^* t^{1-S}) \qquad \text{Eq. 4.10}$$

From Equation 4.9b and 4.10 it follows that $1 \geq S \geq 0$. If S = 0, k_{rav} becomes a constant and equal to R. If S=1, $K_{LI,t} = K_{LI,0,}$ and no removal of K takes place.

4.3. Results

4.3.1. Adsorption

Largest adsorption was by Cang Long soil, followed by Tan An and CLRRI-NP soils (Fig. 4.2). Thoai Son, Binh Phu, Chau Phu and Sediment took a middle position, and least adsorption was in Cau Ke soil. First order equations fitted for K adsorption in the various soils are shown in Table 4.1. R^2 ranged from 0.94 to 0.99, showing that first order kinetics fitted well to K adsorption over time. Measured $K_{L,0}$ [original K(NH_4OAc] and $K_{L,t}$ are shown in Table 3.7 and Annex 4.1, respectively.

The estimated K_0 found by first order equations were relatively high, suggesting that during the initial moistening of the soil, K was rapidly adsorbed. The initial moistening of the soil should have been done with demineralized water.

The rate coefficient for adsorption (k_a) was highest in Cau Ke soil and Sediment (3.73-4.60), and lowest in Cang Long (1.66). Cau Ke and Sediment had low CEC, whereas Cang Long soil had high CEC and also high organic C. For the other soils the rate coefficients for adsorption ranged between 2.0 to 3.0 d^{-1}. Rate coefficients were related to CEC, but R^2 was low (Table. 4.2). Maximum adsorption

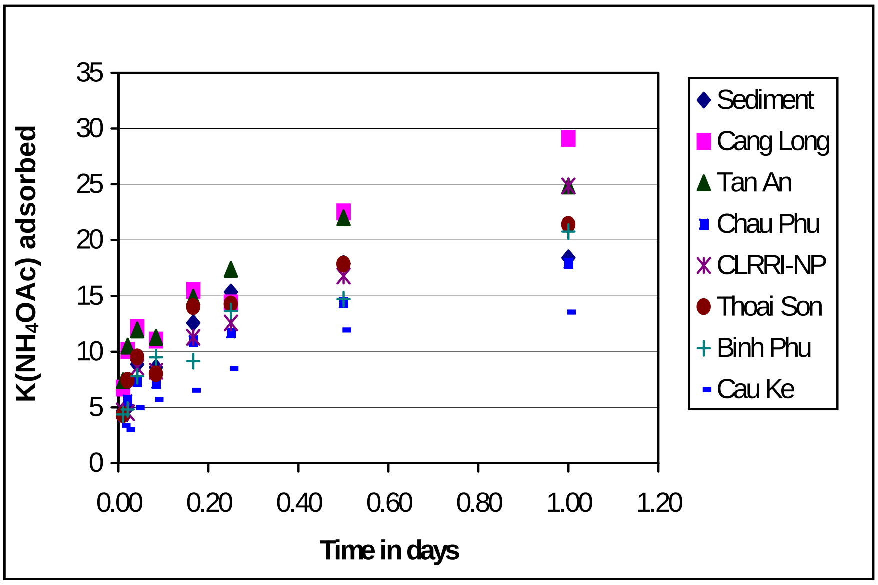


Figure 4.2: Quantities of adsorbed K as determined as K(NH_4OAc) (mmol kg^{-1}), in relation to adsorption time.

was positively related to organic C and clay fractions and also to CEC, which could explain 85% of the differences in maximum adsorption of the soils (Table 4.2).Because K_{max} was positively related to CEC, and k_a negatively related to K_{max} (Eq. 4.1 and 4.2), k_a must be negatively related to CEC.

4.3.2. Fastening

The soil with the highest capacity to fasten K was Tan An (Fig. 4.3). CLRRI-NP, Binh Phu and Cau Ke soils showed low capacity to fasten K, and Chau Phu, Sediment, Cang Long and Thoai Son were in between.

The R^2 of the first order equations fitted for K fastening ranged from 0.96 to 0.99 for the overall reactions from 15 min to 1440 min (Table 4.1). It was observed that during the first hour, from 0.01 to 0.042 d, the rate of fastening was faster, so for that period a separate first order equation was fitted (Table 4.1). The fast reaction can be attributed to the external surface of organic and inorganic phases of the soils, which are readily accessible for cation exchange. The slow reaction represents K fastening on to the less accessible sites of organic matter and interlayer sites of the 2:1 clay minerals in the soil, as also suggested by Sparks (1987). The quantity of K

Table 4.1: Values of R^2 and coefficients of Equation 4.2, used for describing K adsorption ($K(NH_4OAc)$) and fastening ($K(NaTPB)$), and maximum amount of K adsorption and K fastening (K_{max}) (mmol kg^{-1}). Regression coefficients are rate constants for adsorption (k_a) and fastening (k_f). K_0 was calculated from the intercept $\ln(K_{max}-K_0)$. Original K_0 was initially measured $K(NH_4OAc)$ of the soil samples. Ratio of K fastening was calculated as the ratio of measured K_{LI} at 0.042 (1hr) and at 1 day.

	R^2	k (d^{-1})	K_0	Original K_0	K_{max}
$K(NH_4OAc)$					
Overall reaction (0.01-1 d)					
Sediment	0.97	4.60	6.16	3.09	18.59
Cang Long	0.98	1.66	8.12	4.34	33.91
Tan An	0.99	2.99	8.28	4.03	25.74
Chau Phu	0.99	2.29	5.19	1.84	19.34
CLRRI-NP	0.97	2.00	5.46	1.55	23.63
Thoai Son	0.97	2.84	6.04	1.39	22.32
Binh Phu	0.94	2.17	4.96	1.28	22.59
Cau Ke	0.99	3.73	2.09	0.89	13.79
K(NaTPB)					
Overall reaction (0.01-1 d)					
Sediment	0.98	1.90	19.00	10.83	46.25
Cang Long	0.98	2.45	23.37	16.14	43.87
Tan An	0.99	2.45	27.28	20.04	54.39
Chau Phu	0.98	3.13	22.86	13.80	45.28
CLRRI-NP	0.98	2.39	15.51	9.51	25.58
Thoai Son	0.99	3.63	18.97	13.34	37.15
Binh Phu	0.97	3.20	1.61	5.85	25.90
Cau Ke	0.96	4.27	5.16	4.18	19.46
Fast reaction (0.01-0.042 d)					Ratio of K fastening
Sediment	0.99	9.19	13.46	10.83	0.57
Cang Long	0.96	7.13	19.33	16.14	0.60
Tan An	0.98	8.69	20.61	20.04	0.59
Chau Phu	0.96	12.66	15.01	13.80	0.61
CLRRI-NP	0.99	7.85	13.15	9.51	0.67
Thoai Son	0.99	9.55	15.61	13.34	0.62
Binh Phu	0.90	3.30	4.57	5.85	0.28
Cau Ke	0.93	10.65	5.59	4.18	0.56

Table 4.2: Regression analysis for maximum values and rate constants of K adsorption (K(NH_4OAc)) and K fastening (K(NaTPB)) in soils.

Equations are of the shape: $y = a + bx_1 + cx_2$.

Regression equation [a]	Probability of F test				R^2	R^2(adj)
	Equation	a	b	c		
Adsorption						
K_{max} = 6.96 +0.196*org C + 0.018 * clay	0.009	0.123	0.012	0.052	0.85	0.79
K_{max} = 12.6 + 0.059 CEC [b]	0.058	0.017	0.058	-	0.55	0.45
k_a = 3.73 – 0.008 * CEC [c]	0.147	0.004	0.147	-	0.37	0.24
Fastening						
K_{max} = -26.3 + 0.104*silt + 1.79*K(NaTPB)	0.002	0.167	0.057	0.003	0.91	0.88
k_f = 9.29 – 0.016* silt	0.009	0.002	0.009	-	0.70	0.65

[a] K_{max} and CEC were expressed in mmol kg^{-1}, org.C clay and silt in g kg^{-1}, and k_a and k_f in d^{-1}.

[b] Cang Long soil was not included in the calculation of the regression equation

[c] Sediment was not included in the calculation of the regression equation

fastened during the first hour was on average 60% of the total amount of K fastened during 24 hours. Measured $K_{L,0}$ [original K(NaTPB] and $K_{LI,t}$ are shown in Table 3.7 and Annex 4.1, respectively.

Maximum quantity of fastened K was related to silt and original K(NaTPB) contents of the soils (Table 4.2). Both, K(NaTPB) and silt, are indicators for K at inner or interlayer positions, especially for soils in the Mekong Delta of which the clay fraction is high in illite (Guong, 2000) and the silt fraction is high in mica (Uehara, 1974). The mineralogy therefore can explain the behavior of the soils with respect to K fastening.

Fastening rate (k_f) was negatively related to silt content (Table 4.2), suggesting that soils with high silt fraction in this study slowly fasten K due to the less accessibility of the inner positions of mica in the silt fraction. Because K_{max} was positively related to silt content and k_f negatively related to K_{max} (Eq. 4.1&4.2), k_f must be negatively related to silt content. This is similar situation as between k_d and CEC (Section 4.3.1).

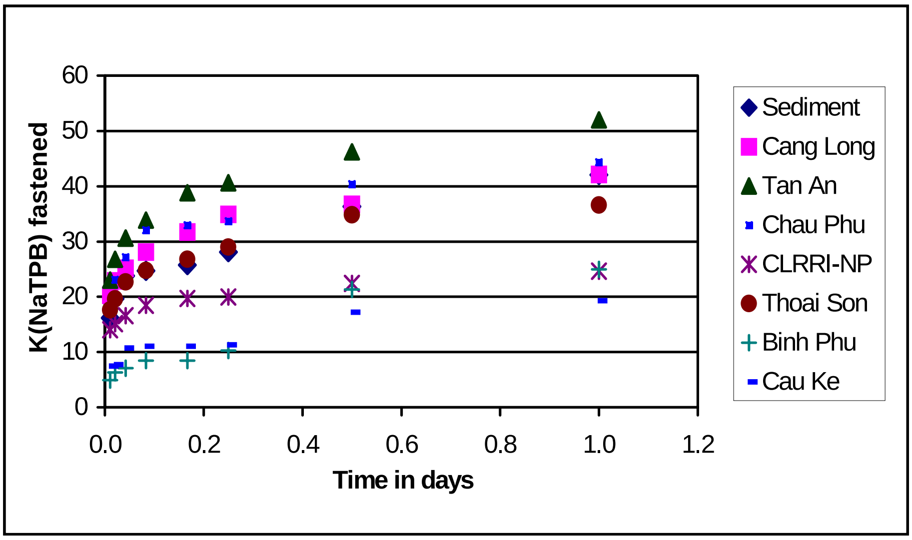


Figure 4.3: Quantities of fastened K determined as K(NaTPB) (mmol kg^{-1}) in relation to fastening time.

4.3.3. Desorption

The fitting of a first order equation to the experimental results of K desorption in soils suggested that for short leaching periods (15 to 360 min), the desorption rate coefficient (k_d) could be described as a constant value (Table 4.3). The desorption rate constants were found to be highest for Sediment, and Cang Long, medium in Binh Phu and CLRRI-NP and lowest in Thoai Son and Tan An. (Table 4.3). However, R^2 was low in Chau Phu and Cau Ke soils. In Chau Phu soil, K desorption was very quick at the beginning and decreased thereafter, suggesting that the rate coefficient was not constant for the whole period. Cau Ke soil is an outlier with an irregular pattern of desorption.

Amounts of K desorbed versus time, as calculated by the difference between $K_{L,0}$ and $K_{L,t}$ (both derived from the first order equations), is shown in Fig. 4.4 for all soils (except for Chau Phu and Cau Ke soils because of the lack of fit). The percentage of K desorbed after 6 h leaching calculated as the difference between the calculated values of K remaining in the soil at time t = 6 h ($K_{L,6}$) and K($_{L,0}$), showed that soils could desorb 46-78% of the calculated K_L,$_0$ in 6 hours. Measured $K_{L,0}$ [original K(NH_4OAc] and $K_{L,t}$ are shown in Table 3.7 and Annex 4.2, respectively.

Table 4.3: The fitting of first order equation for describing K desorption by 0.01 M $CaCl_2$, and percentage of K desorption calculated by ratio of maximum desorption in 360 min (calculated K(NH_4OAc)- calculated $K_{L,t}$) and calculated $K_{L,0}$ of the soils.

Soil	R^2	k_d (d^{-1})	Calculated $K_{L,0}$	% K desorption
Sediment	0.94	6.00	2.39	83.4
Cang Long	0.87	4.39	2.32	78.9
Tan An	0.93	2.82	2.12	72.4
Chau Phu	0.83	4.65	1.67	67.8
CLRRI-NP	0.95	3.26	1.12	66.2
Thoai Son	0.91	2.49	1.16	50.7
Binh Phu	0.91	3.50	1.14	71.0
Cau Ke	0.72	5.13	1.43	72.7

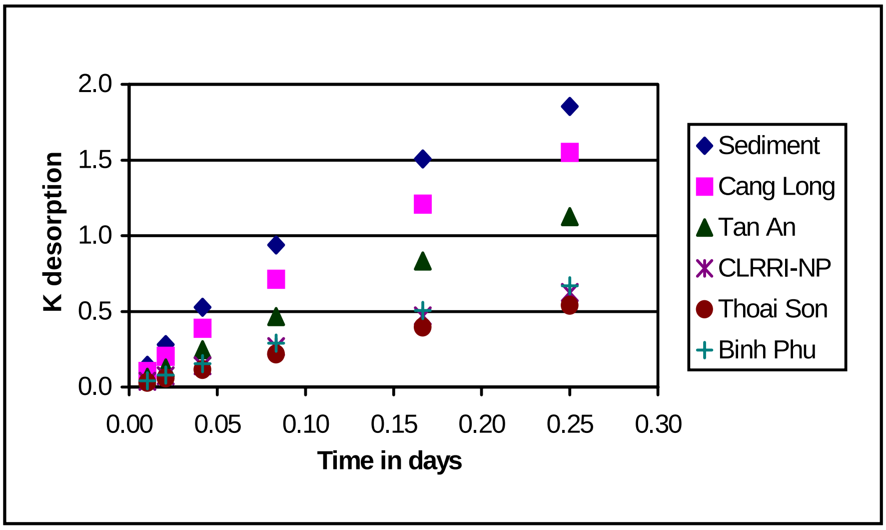


Fig 4.4: K desorption (mmol kg^{-1}) calculated as the difference between $K_{L,0}$ and $K_{L,t}$ (Eq. 4.5b). All values of $K_{L,0}$ and $K_{L,t}$ (Eq.4.5a) were derived from fitted first order equations.

4.3.4. Removal

The first order equations applied to K removal by 0.067M NaTPB during the period from 1 min to 400 hours had a variation in R^2 from 0.78 to 0.92 (Table 4.4). In all soils k_r was in the range of 0.34-1.2 d^{-1} (1.0 $x10^{-2}$ - 5.0 $x10^{-2}$ h^{-1}) for the period between 1min and 144 h. Comparison between calculated and measured amounts of K remaining in the soil at time t showed that the first order equation did not well describe K removal (Fig. 4.5). Further, Figure 4.6 reveals that there was a trend of decreasing k_r rates with time, except for Cau Ke soil, suggesting that k_r varied with time.

Application of the Yang and Janssen equation for describing K removal kinetics showed that there was indeed a linear relationship of ln k_{rav} versus ln t as derived by Eq. 4.9a (see Fig 4.7). Table 4.5 presents the values of k_{rav1}, S and R^2. The values of $K_{LI,t}$ calculated with Eq. 4.10 are compared with measured $K_{LI,t}$ in a 1:1 line graph in Fig 4.8. Measured removed K is shown in Annex 4.3.

Table 4.4: Values of R^2 and k_r for first order equations for K removal by 0.067 M NaTPB and percentage of K(total) in 400 hours.

Soil	R^2	k_r (d^{-1})	% total K removed
Sediment	0.92	0.78	30
Tan An	0.90	1.20	33
Chau Phu	0.84	1.09	32
CLRRI-NP	0.91	0.50	30
Binh Phu	0.78	0.41	24
Cau Ke	0.86	0.34	28

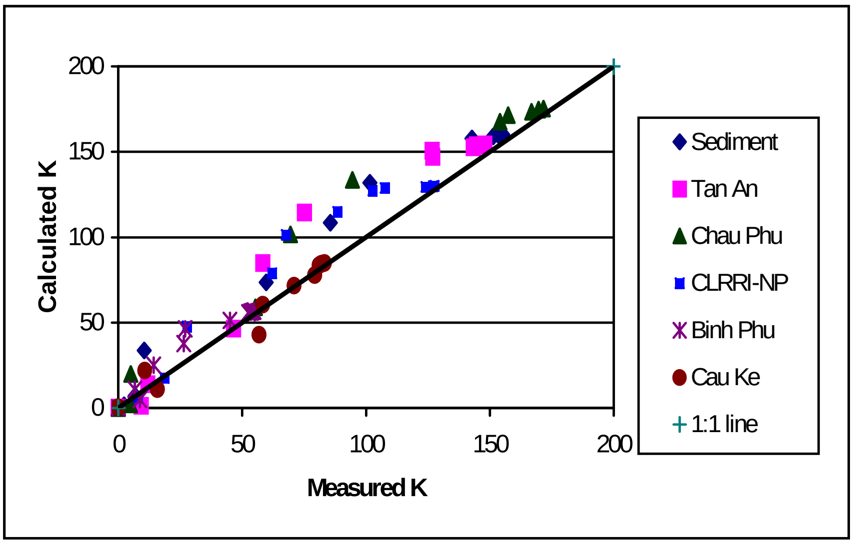


Figure 4.5: Comparison of measured values of $K_{LI,t}$ (mmol kg^{-1}) after extraction with 0.067 M NaTPB, with values calculated by first order equation (Eq.4.7a) .

Table 4.5: Values of k_{rav1}, S and R^2 of the relations between ln k_{rav} and ln t.

	k_{rav1}	S	R^2
Sediment	1.19	0.42	0.93
Tan An	1.59	0.44	0.94
Chau Phu	1.43	0.35	0.92
CLRRI-NP	1.05	0.43	0.94
Binh Phu	1.34	0.47	0.92

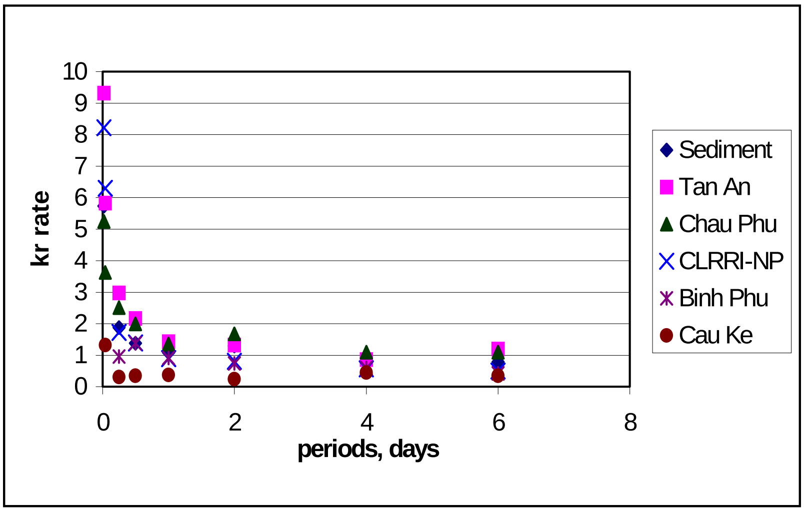


Figure 4.6: Value of k_r rate, as calculated by first order equations for different time periods. The first values refer to a period of 0.5h or 0.02 d.

The Yang and Janssen equation could very well describe the kinetics of K removal by 0.067 M NaTPB.

The quantities of K removed (Fig 4.9) were highest for Chau Phu, Sediment, Tan An, intermediate to low for CLRRI-NP and lowest for Binh Phu soil. Binh Phu soil is a kaolinitic clay soil, where K removal is expected to be low. CLRRI-NP soil had been mined for K during 12 crops without K fertilizer, and may therefore show low K removal.

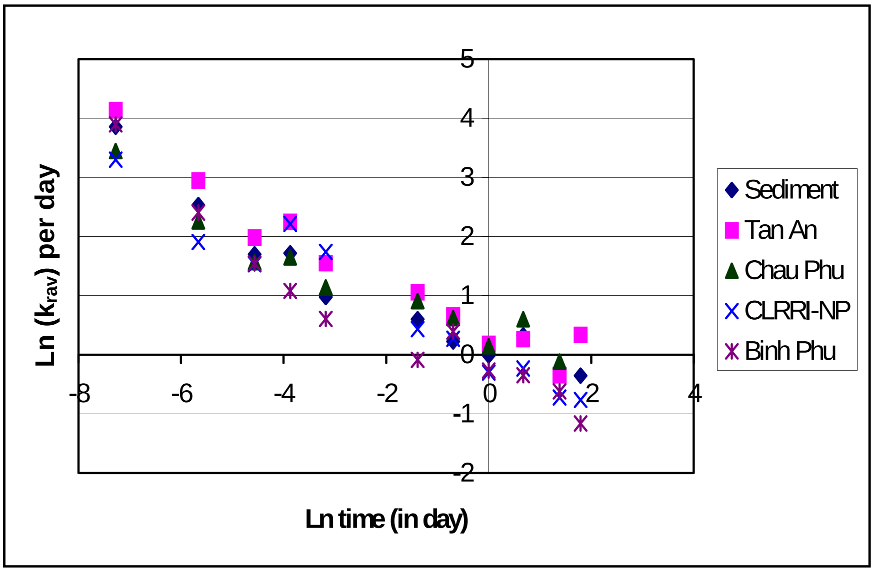


Figure 4.7: Relation between ln(k_{rav}) and ln time. The first values refer to 0.017 h or 0.001 d.

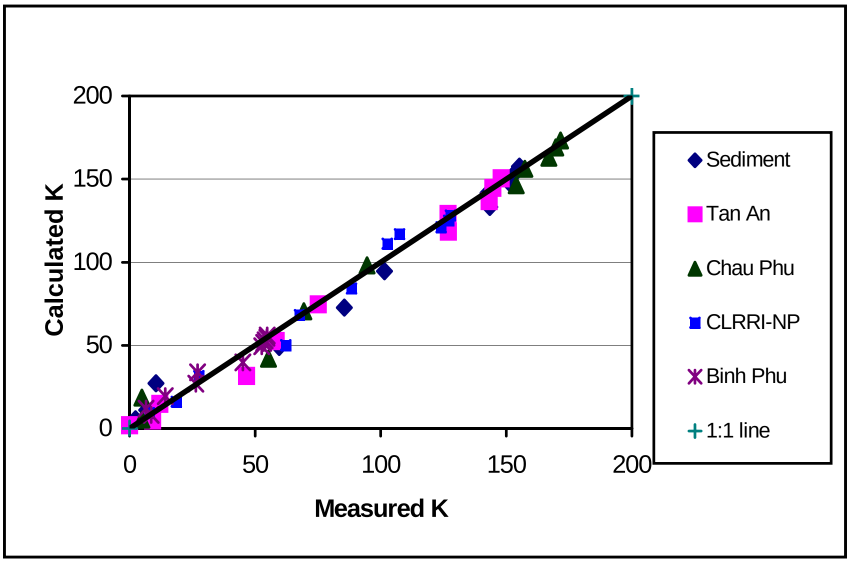


Figure 4.8: Comparison of measured values of $K_{LI,t}$ with values calculated by Yang and Janssen equation (Eq.4.10). The solid line represents the 1:1 line.

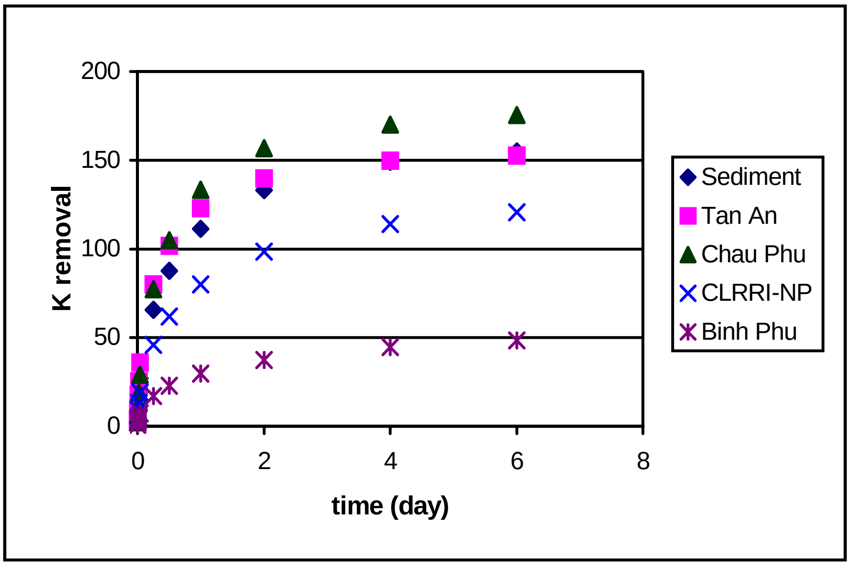


Figure 4.9: K removed by 0.067 M NaTPB in the course of time (mmol kg^{-1}) as described by Yang and Janssen equation. (Eq.4.7b)

The average k_r rate at day 1 (k_{rav1}) or initial average removal rate was correlated with K(NH_4OAc) for 4 soils (Fig. 4.10), and with K(NaTPB) for all soils (Fig.4.11). The relation of the rate of decresae of average k rate (S) and initial average k rate (k_{rav1}) may provide some more information on the rate of decrease in k_{rav} (Fig. 4.12). In general, it can be seen from Fig. 4.12, that the decrease in k_{rav} is faster for soils low in k_{rav1} than for soils high in k_{av1}. The relations of Fig. 4.10, 4.11 and 4.12 suggest that soils with high K(NaTPB) have a higher rate of K removal, and can maintain that rate over a longer period than soils with low K(NaTPB). The removal of K by 0.067 M NaTPB, expressed as percentage of total K ranged from 12 to 23% after 24 hours and from 30% to 33% after 400 hours in the young alluvial soils tested (Sediment, Tan An, Chau Phu and CLRRI). Binh Phu old alluvial soil had a removal as low as 24% after 400 hours. This range is lower than the highest values reported by Lin (1978) in rice soils in Taiwan, which removed 25-37% of total K as extracted by 0.3 M NaTPB in 16 hours, but it is in the middle of their total range (10.6-18.0%).

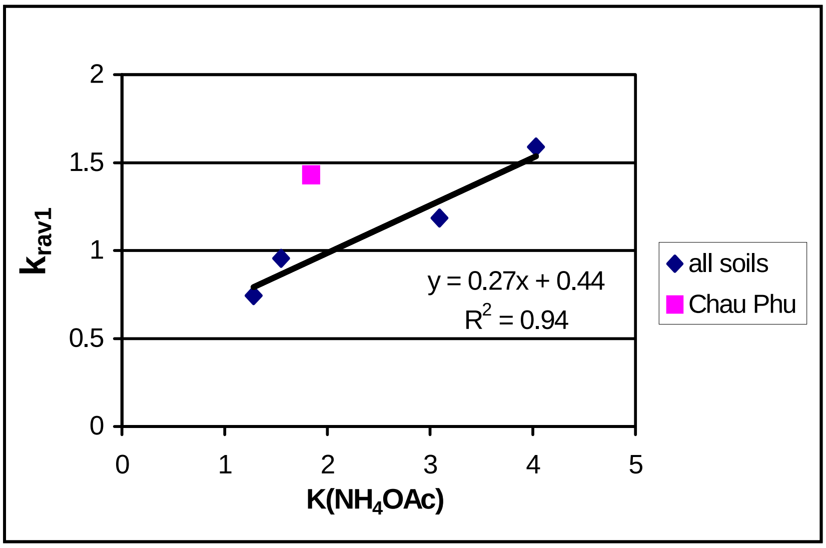


Fig 4.10: Relation between k_{rav1} and K(NH_4OAc). Chau Phu soil is not included in the regression equation.

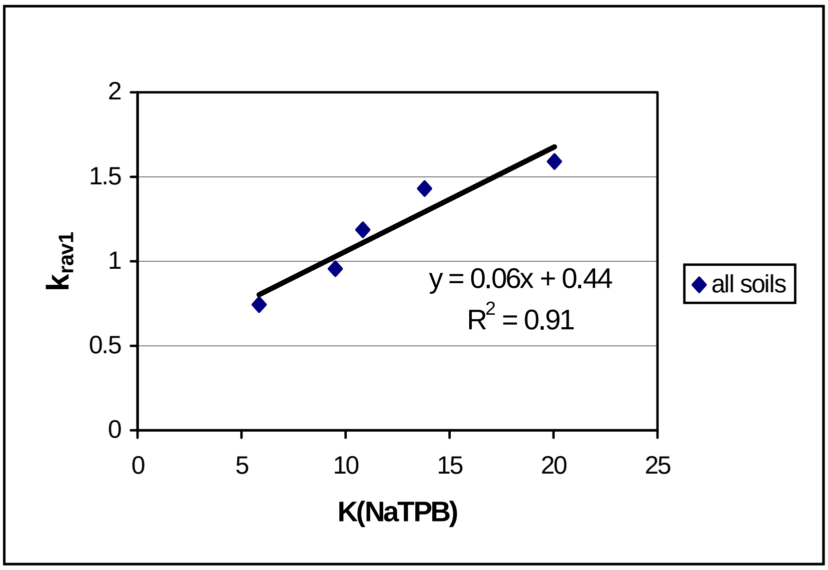


Fig 4.11: Relation between k_{rav1} and K(NaTPB) for all soils.

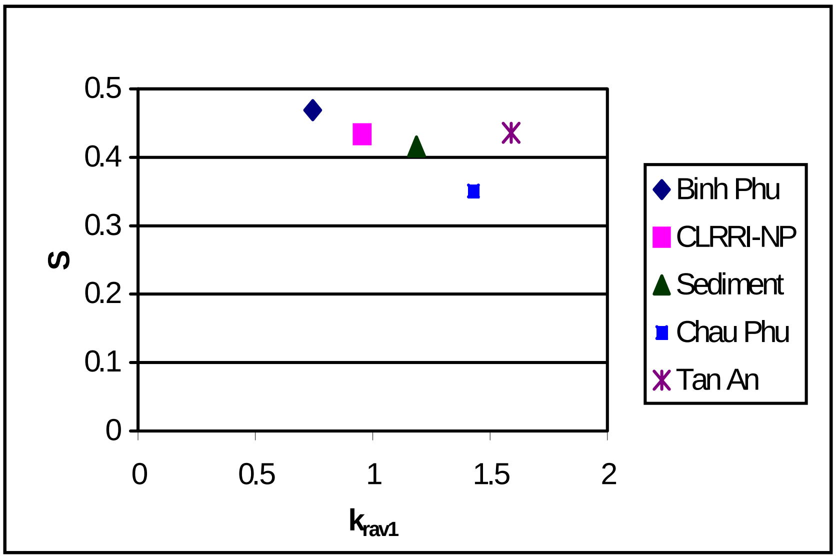


Figure 4.12: Relation between rate of decrease in k_{rav} (S) and initial average removal rate coefficient (k_{rav1})

4.4. Discussion and Conclusions

A first order equation with constant coefficient could well describe K adsorption, as determined in our experiments. Two first order equations had to be used to describe properly the fastening of K, as determined in our experiments. The first equation represents the fast reaction from 0.01-0.042 day (15-60 min) for the ready accessible external surface sites of organic and inorganic phases, and the second equation represents the overall reaction from 0.01-1 day (15-1440 min) including both fast and slow reactions. The slow reaction is attributed to less accessible sites of organic matter and interlayer sites of the 2:1 clay mineral (Sparks, 1987).

The adsorption capacity of the studied soils was related to the clay and organic C contents of the soils, whereas the fastening capacity was related to silt content and K(NaTPB). It is generally considered that among clay and other silicates, micas and vermiculite have a high and montmorillonite and kaolinite have a low K fixation capacity (Shaviv et al., 1985; Sardi and Csitari, 1998). In this study, the predominance of kaolinite in Binh Phu, and the loamy texture in Cau Ke can explain the low K fastening of these soils. The moderate fastening of K in CLRRI-NP soil, however, was not expected because the soil had been mined for K by 12 crops without K fertilizer additions.

Desorption of labile K by 0.01 M $CaCl_2$ could be described well with a first order equation with constant rate coefficient. However, the removal by 0.067M NaTPB, which creates a zero sink for K and extracts K from interlayer position, proceeded at a decreasing rate, for which the ‘Yang and Janssen’ first order equation with variable rate coefficient showed a better fit.

In their study of K release kinetics by 0.2 M NaTPB in 7 days, Cox and Joern (1997) concluded that the Elovich and simplified Elovich equations were well suited to describe K removal. However, neither forms of the Elovich model could describe the early phase of K removal by 0.2 M NaTPB adequately. They also found that K removal was fitted well by power function ($q = k \ln t^b$; where q is amount of non-exchangeable K removed at time t, and k and b are empirical constants), and that the product of the two constants (k * b), which has also been considered as an initial removal k index, can be an indicator of K supplying power in the soils. But they emphasized that this function did not suggest any particular removal mechanism.

The Yang and Janssen first order equation with variable rate coefficient proved to fit very well K removal over time, revealing that the rate of K removal was not constant, but decreased over time. It suggests that there are numerous gradations in terms of ease of K removal. The reason why ordinary first order equations with constant rate coefficient are suitable for describing adsorption (and fastening) and desorption, but not for K removal is basically because of the heterogeneity of the K pools and especially of the retention sites in the interlayers and, hence, in the removal mechanisms. The adsorption and desorption processes represent processes that occur at external surfaces. These processes are usually rapid and depend only on the amount of “open” planar sites for adsorption and the amount of K at planar sites for desorption. The removal process, however, represents in part processes that occur at the interlayer space, where different retention forces are involved (Mc Lean and Watson, 1985; Sparks, 2003). Therefore the removal process is dependent on the ease of the removal of K from multiple sites. The decrease of the removal rate coefficient over time can be detected by a zero sink like NaTPB.

The good relations between initial average k rate (k_{rav1}) and K(NH_4OAc) and between k_{rav1} and K(NaTPB), and between S and the steepness of the decrease in k_{rav1}, also indicate that K(NH_4OAc) and K(NaTPB) are good predictors for the K supplying power in the soils tested. However, the Yang and Janssen equation was tested with only few soils in this study. More studies are needed to verify whether the equation is generally applicable for the description of K removal in soils.

CHAPTER 5:

SOIL K CHANGES IN RESPONSE TO K FERTILIZATION, K UPTAKE BY RICE, AND WATER MANAGEMENT

5.1. Introduction

It is generally agreed that soils supply K to plants mainly from both the exchangeable and non-exchangeable K pools in soils (Gholston and Hoover, 1948; Reitemeier, 1951; Pearson, 1952; Addiscott and Johnston, 1975; Goulding; 1984; Dhillon et al, 1989; Cox et al., 1999, Pal et al. 2001). Exchangeable K, as determined by 1 M NH_4OAc is usually defined as labile K (LK) and non-exchangeable K, determined by the difference between K(NaTPB) and K(NH_4OAc) or net K(NaTPB) is defined as intermediate K (IK). In Chapter 3, K(NH_4OAc) and K(NaTPB) have been found to be well related to total uptake by rice plants. In the current study, it was hypothesized that labile K and intermediate K could represent the first and second pool of a three-pools model on soil K dynamics under cropping conditions. Two versions of such a three-pools model are shown in Fig 5.1 and Fig. 5.2.

In the Mekong Delta, intensive triple rice crop system is depleting soil K. Although sediments can supply large amounts of K(NH_4OAc) and K(NaTPB), K balances in these areas were negative for dissolved K, K(NH_4OAc) and K(NaTPB) (Chapter 2). However, it is not known how rapid these K pools will get depleted. This was investigated in a controlled input-output three-rice-crops-cycle in a greenhouse experiment where plant K uptake and changes in labile K and intermediate K in soil were measured, and subsequently evaluated in simple model calculations, using the models depicted in Figure 5.1 and 5.2.

Water management (wet or dry) during the period between two successive rice crops can affect the bonding of K to soil. Chen et al. (1987) reported that K fixation is enhanced by the reduction of octahedral Fe^{3+} in the clay crystal. Khaled and Stucki (1991) concluded that chemical reduction of structural Fe^{3+} to Fe^{2+} in the octahedral sheet of dioctahedral smectites causes an increase in fixation of interlayer K. The strong interlayer forces, which ultimately arise from Fe^{3+} reduction, may cause layers to collapse, and thus trap interlayer cations.

Objectives of the study described in this chapter were (i) to study the changes of K(NH_4OAc) and K(NaTPB) in fertilized and unfertilized soils, following K uptake by successive rice crops, (ii) to verify the appropriateness of 0.2 M NaTPB 5 min as extraction procedure for determining the sum of labile and intermediate K pools in the models shown in Fig 5.1 and Fig 5.2, and (iii) to investigate the effect of water management during periods in between two crops on the changes of K(NH_4OAc) and K(NaTPB) in soils.

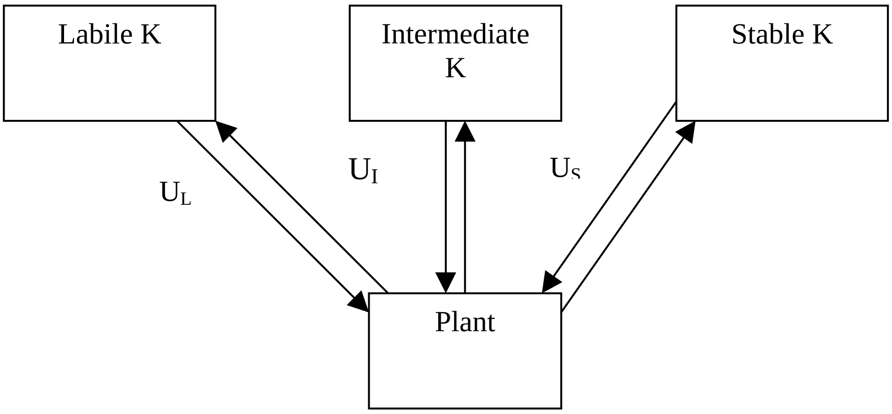


Figure 5.1: Parallel model with 3 soil K pools. The codes of the flows are explained in Table 5.1 and the text. Flows without codes are not discussed.

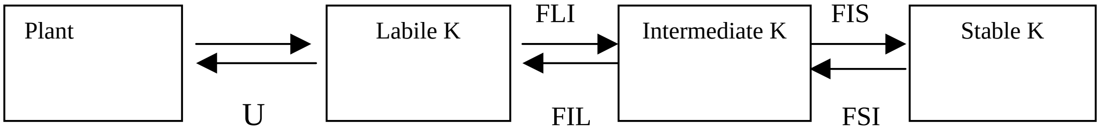


Figure 5.2: Series model with three soil K pools. The codes of the flows are explained in Table 5.1 and the text. Flows without codes are not discussed.

5.2. Materials and Methods

5.2.1. Experimensts

The greenhouse experiment with successive rice crop cycles was carried out at the University of Can Tho in Vietnam. A crop cycle lasted 95 days. Between two crops, soil remained without plants for 25 days. Six cycles had been planned originally, but because of the poor plant growth in pots not receiving fertiliser K, the number of cycles was reduced to three. The design of the experiment was a 4*2*2 factorial in 3 replicates. The first factor was soil type. Four soils were used: Soil 7 (CLRRI-NP), Soil 12 (Binh Phu), Soil 17 (Cau Ke) and Soil 18 (An Cu) (Tables 3.3 & 3.4). The second factor was fertiliser K application: 0 and 800 mg K per pot per crop. The third factor was water management between crops: keeping soil wet or dry. In wet management treatments, soils remained flooded during the 25 days between successive crops, whereas in dry management treatments, soils were let to dry during those 25 days. After 25 days of flooding in wet management, water was removed and was added back after sowing rice. Each pot was filled with four kilogram of soil on an air-dried basis. Fifteen seeds were sown in each pot and seedlings were thinned to 6 plants at 7 days after sowing. Nitrogen fertiliser was applied at a rate of 200 mg N in the first crop; the rate was reduced to 150 mg N in the second and the third crop because yellow dwarf disease was observed in the first crop. Fertiliser N was split applied at 0, 25 and 40 days after sowing. Per crop 50 mg P was applied at the day before sowing. Also at the day before sowing K was applied all at once. A ten times diluted Hoagland and Arnon solution No. 2 (Salisbuny and Ross, 1992) was applied in all soils each 2 weeks during the first crop. In the second and the third crop, it was only applied in Cau Ke loamy and An Cu sandy soils because Fe toxicity was observed in Binh Phu soil in the first crop and to a lesser degree in the second and third crop. The toxic problem was observed in Binh Phu soil, but not in CLRRI soil, perhaps due to the high easily reducible Fe content in Binh Phu soil. The above plant parts were harvested, oven-dried at 70^{o}C, weighed, ground, and analyzed for K. Uptake of K was calculated as the product of dry mass and K mass fraction, and to find K uptake from the soil, K in seeds was subtracted from the calculated total uptake. The roots remained in the pot. At the beginning and at the end of each crop, a representative soil sample of about 45g was taken for analysis of K(NH_4OAc). At the beginning of the first crop and at the end of the third crop samples were also analysed for K(NaTPB). Grain yield, K application and K uptake were expressed per kg of soil, using the corrected amounts of soil present in the pot at the start of each crop cycle.

5.2.2. Calculation of K flows

In order to improve the understanding of the changes of soil K pools during the experiment, it was tried to calculate the K flows between pools and crops. The flows between soil pools are denoted by three letters, the first is always F, and the next two letters stand for the pool from where the flux departs and where the flux arrives, respectively (Table 5.1). The flow of K between soil pools and the crop is denoted by U, with a subscript indicating the pool from which the crop took up the K. The basic information used consisted of the initial and final values of K(NH_4OAc) and K(NaTPB), the initial value of total K, and K uptake by the three crops. Initial values are denoted by subscript b, and the final values by subscript e; the subscript f stands for fertilized and refers to situations where fertiliser K had been added.

Table 5.1 lists the equations used. The flows were calculated for the so-called parallel model and the series model. Further justifications for these models are presented in Chapter 6. The pools and flows are shown in the schematic drawings of

Table 5.1. Equations for the calculation of pools and flows of K according to the Parallel and the Series conceptual models. For explanation see text.

	Equation		
Name	Code	Description	Number
Pool			
Labile K	LK	$K(NH_4OAc)$	5.1
Intermediate K	IK	$K(NaTPB) - K(NH_4OAc)$	5.2
Stable K	SK	Total K - K(NaTPB)	5.3
Labile K after K addition	LK_{bf}	LK_b + 0.75 Fertiliser K	5.4
Intermediate K after K addition	IK_{bf}	IK_b + 0.25*Fertiliser K	5.5
Total K after K addition	TK_{bf}	Total K_b + Fertiliser K	5.6
Total K end	TK_e	Total K_b - U	5.7
Flow			
	Parallel		
Uptake from LK	U_L	$LK_b – LK_e$	5.8
Uptake from IK	U_I	$IK_b – IK_e$	5.9
Uptake from SK	U_S	$SK_b – SK_e$	5.10
Pool or Flow			
	Series		
Stable K at end	SK_e	$SK_b – FSI + FIS$	5.11a
Net flow from SK to IK	FSI - FIS	$SK_b – SK_e$	5.11b
Intermediate K at end	IK_e	$IK_b + FSI – FIS + FLI - FIL$	5.12a
Net flow from IK to LK	FIL – FLI	$IK_b – IK_e + FSI – FIS$	5.12b
Labile K at end	LK_e	$LK_b + FIL – FLI - U$	5.13a
Uptake from LK	U	$LK_b - LK_e + FIL – FLI$	5.13b

the models (Figures.5.1 & 5.2). In both models, three pools are distinguished: labile (LK), intermediate (IK) and stable K (SK). LK is equal to K(NH_4OAc), IK and SK are calculated with Eq. 5.2 and 5.3 (Table 5.1). Because K fertilisers do easily dissolve, they can react immediately with the soil components. Based on the results of Chapter 4, it was decided to allocate 75% of added K to LK (Eq. 5.4) and 25% to IK (Eq. 5.5). Of course 100% of added K is found in Total K (Eq. 5.6). At the end of the experiment, Total K was not measured again, and hence TK_e had to be calculated (Eq. 5.7).

In the Parallel Model, no flows among the soil K pools do exist, and the uptake from the pools is simply calculated as the difference in pool size between the beginning and the end of the experiment (Eqs. 5.8, 5.9 and 5.10).

In the Series Model, flows among the soil K pools were calculated on the basis of the changes in pool sizes. Given the design of the experiment, it was not possible to find each individual flow. Only the net effect of forward and backward flows could be calculated (Eqs. 5.11b, and 5.12b).

Because uptake is a term in the equation for the calculation of TK_e (Eq. 5.7), the final calculation of total uptake (sum of Eqs. 5.8, 5.9 and 5.10 in the Parallel Model, Eq. 5.13b in the Series Model) served as a check only.

5.3. Results

5.3.1. Yield and K uptake

Results of rice yield, straw yield, K mass fractions in grain and straw, and plant uptake are shown in Tables 5.2-5.6. Analysis of variance showed that there was no effect of wet and dry water management on all plant data in Crop 1 and Crop 2. In Crop 3 grain yield was significantly higher in wet management than in dry management in CLRRI and Binh Phu fertilized soils, while only in Binh Phu

Table 5.2: Grain yield (g kg^{-1} soil) at 14% moisture content, as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

Water management	Fertiliser	Soil	Crop 1	Crop 2	Crop3	Sum
Wet	0K	CLRRI-NP	8.49	1.27	0.55	10.31
		Binh Phu	2.93	1.42	1.10	5.45
		Cau Ke	6.24	0.70	0.37	7.31
		An Cu	2.79	0.77	0.78	4.34
		Mean 0K	*5.11*	*1.04*	*0.70*	*6.85*
	+K	CLRRI-NP	12.81	8.29	7.16	28.26
		Binh Phu	7.5	5.27	5.24	18.01
		Cau Ke	9.44	7.31	5.49	22.24
		An Cu	6.21	6.07	4.84	17.12
		Mean +K	*8.99*	*6.74*	*5.68*	*21.41*
	Mean (wet)		**7.05**	**3.89**	**3.19**	**14.13**
Dry	0K	CLRRI-NP	6.84	1.14	0.96	8.94
		Binh Phu	4.43	1.06	1.22	6.71
		Cau Ke	5.65	0.86	0.79	7.30
		An Cu	3.27	0.68	0.34	4.29
		Mean 0K	*5.05*	*0.94*	*0.83*	*6.81*
	+K	CLRRI-NP	13.98	8.32	6.06	28.36
		Binh Phu	6.22	5.77	4.21	16.20
		Cau Ke	8.17	7.31	5.42	20.90
		An Cu	6.42	5.81	3.60	15.83
		Mean +K	*8.70*	*6.80*	*4.82*	*20.32*
	Mean (dry)		**6.87**	**3.87**	**2.83**	**13.57**
F test (W)			ns	ns	*	
F test (K)			**	**	**	
F test (S)			**	**	**	
LSD 5%(WxKxS mean)			2.71	0.89	0.91	

fertilized soil, K uptake in wet management was significantly higher than in dry management.

Table 5.3: Straw yield (g kg^{-1} soil) oven-dried at 70°C as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

Water management	Fertiliser	Soil	Crop 1	Crop 2	Crop3	Sum
Wet	0K	CLRRI-NP	10.6	3.05	1.46	15.11
		Binh Phu	7.59	3.44	2.84	13.87
		Cau Ke	7.87	2.08	1.50	11.45
		An Cu	5.44	3.29	1.80	10.53
		Mean 0K	*7.88*	*2.97*	*1.90*	*12.74*
	+K	CLRRI-NP	15.03	6.16	6.33	27.52
		Binh Phu	9.83	6.25	7.57	23.65
		Cau Ke	11.85	5.95	5.40	23.20
		An Cu	9.14	5.73	4.79	19.66
		Mean +K	*11.46*	*6.02*	*6.02*	*23.51*
	Mean (Wet)		**9.67**	**4.49**	**3.96**	**18.12**
Dry	0K	CLRRI-NP	10.61	3.34	2.38	16.33
		Binh Phu	7.85	3.50	2.45	13.80
		Cau Ke	7.71	2.27	1.76	11.74
		An Cu	6	1.89	1.16	9.05
		Mean 0K	*8.04*	*2.75*	*1.94*	*12.73*
	+K	CLRRI-NP	14.71	6.88	6.28	27.87
		Binh Phu	10.84	5.94	5.53	22.31
		Cau Ke	11.78	5.91	5.06	22.75
		An Cu	10.49	5.34	4.17	20.00
		Mean +K	*11.96*	*6.02*	*5.26*	*23.23*
	Mean (dry)		**10.00**	**4.38**	**3.6**	**17.98**
F test (W)			ns	ns	*	
F test (K)			**	**	**	
F test (S)			**	**	**	
LSD 5% (W*K*S mean)			1.60	0.97	1.17	

Application of K fertiliser gave significant effects on grain yield, straw yield, K mass fractions in straw and K uptake in all 3 crops. In general, K mass fractions in grain were comparable in fertilized and unfertilized soils. K mass fractions in straw were very low (2.6 – 5.5 g kg^{-1}) in the first crop in unfertilised soils, suggesting K

Table 5.4: Grain K mass fraction (g kg^{-1}), as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

Water management	Fertiliser	Soil	Crop 1	Crop 2	Crop3
Wet	0K	CLRRI-NP	2.20	3.20	3.60
		Binh Phu	2.00	3.60	3.50
		Cau Ke	2.60	3.60	4.10
		An Cu	2.60	3.70	3.90
		Mean 0K	*2.35*	*3.53*	*3.78*
	+K	CLRRI-NP	2.80	3.00	3.00
		Binh Phu	1.80	3.30	3.50
		Cau Ke	3.40	2.90	3.80
		An Cu	2.60	3.40	4.10
		Mean +K	*2.65*	*3.15*	*3.60*
	Mean (wet)		**2.50**	**3.34**	**3.69**
Dry	0K	CLRRI-NP	1.90	3.70	3.60
		Binh Phu	2.50	3.30	3.40
		Cau Ke	2.70	3.40	3.80
		An Cu	2.90	3.90	4.40
		Mean 0K	*2.50*	*3.58*	*3.80*
	+K	CLRRI-NP	3.00	3.10	3.20
		Binh Phu	1.80	3.50	2.90
		Cau Ke	3.10	3.10	3.90
		An Cu	3.40	3.40	4.00
		Mean +K	*2.83*	*3.28*	*3.50*
	Mean (dry)		**2.66**	**3.43**	**3.65**
F test (W)			ns	ns	ns
F test (K)			ns	**	ns
F test (S)			**	*	*
LSD 5% (W*K*S mean)			0.09	0.04	0.12

deficiency even in the first crop. In the second and third crops, K mass fractions were even lower suggesting severe K deficiency. Plants almost stopped growing, and grain yield and straw yield were very low in unfertilised soils. In fertilized soils, K mass fractions in straw were still low in CLRRI-NP and Binh Phu soils

Table 5.5: Straw K mass fraction (g kg^{-1}), as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

Water management	Fertiliser	Soil	Crop 1	Crop 2	Crop3
Wet	0K	CLRRI-NP	3.40	1.70	2.70
		Binh Phu	3.80	1.40	2.00
		Cau Ke	2.90	2.10	3.40
		An Cu	5.50	2.00	2.80
		Mean 0K	3.90	1.80	2.73
	+K	CLRRI-NP	9.30	16.70	19.00
		Binh Phu	10.50	15.10	20.10
		Cau Ke	13.30	20.20	18.50
		An Cu	14.90	23.30	20.60
		Mean +K	12.00	18.83	19.55
	Mean (wet)		7.95	10.31	11.15
Dry	0K	CLRRI-NP	4.10	1.10	1.80
		Binh Phu	2.60	1.50	1.50
		Cau Ke	3.40	1.30	2.50
		An Cu	5.30	1.30	3.30
		Mean 0K	3.85	1.30	2.28
	+K	CLRRI-NP	10.90	18.40	19.10
		Binh Phu	8.90	17.50	19.60
		Cau Ke	13.60	19.00	19.50
		An Cu	15.20	22.40	18.40
		Mean +K	12.15	19.33	19.15
	Mean (dry)		8.00	10.31	10.72
F test (W)			ns	ns	ns
F test (K)			**	**	**
F test (S)			**	*	ns
LSD 5% (W*K*S mean)			0.19	0.19	0.14

(8.9-10.9 g kg^{-1}) in the first crop, but increased in the second and third crops (15.1-23.3 g kg^{-1}) due to continuous K application.

Table 5.6: Uptake (mmol kg^{-1} soil), as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

Water management	Fertiliser	Soil	Crop 1	Crop 2	Crop3	Sum
Wet	0K	CLRRI-NP	1.35	0.23	0.14	1.72
		Binh Phu	0.88	0.23	0.23	1.34
		Cau Ke	0.98	0.17	0.13	1.28
		An Cu	0.92	0.25	0.20	1.37
		Mean 0K	*1.03*	*0.22*	*0.18*	*1.43*
	+K	CLRRI-NP	4.45	3.22	3.57	11.24
		Binh Phu	2.98	2.84	4.32	10.14
		Cau Ke	4.81	3.59	3.05	11.45
		An Cu	3.83	3.92	2.99	10.74
		Mean +K	*4.02*	*3.39*	*3.48*	*10.89*
	Mean (wet)		**2.53**	**1.81**	**1.83**	**6.16**
Dry	0K	CLRRI-NP	1.40	0.19	0.19	1.78
		Binh Phu	0.78	0.21	0.18	1.17
		Cau Ke	1.02	0.15	0.18	1.35
		An Cu	1.04	0.12	0.10	1.26
		Mean 0K	*1.06*	*0.17*	*0.16*	*1.39*
	K	CLRRI-NP	5.09	3.81	3.52	12.42
		Binh Phu	2.74	3.14	3.21	9.09
		Cau Ke	4.62	3.42	3.01	11.05
		An Cu	4.73	3.55	2.28	10.56
		Mean +K	*4.30*	*3.48*	*3.01*	*10.78*
	Mean (dry)		**2.68**	**1.82**	**1.58**	**6.08**
F test (W)			ns	ns	*	
F test (K)			**	**	**	
F test (S)			**	*	**	
LSD 5% (W*K*S mean)			0.73	0.43	0.52	

In general, growth was better in CLRRI-NP soil than in the other soils, in both fertilized and unfertilized condition. In Binh Phu soil, K uptake in the first crop was lower than in the other soils. Considering all crops together, An Cu soil had lowest grain yield, straw yield and K uptake, probably because of the poor fertility status of this sandy soil.

5.3.2. Soil K

K(NH_4OAc) measured at the beginning and at the end of each crop and K(NaTPB) measured at the end of Crop 3 were not significantly affected by water management (Table 5.7). Exception was on An Cu soil at the beginning of Crop 3 in fertilized soil, where K(NH_4OAc) in dry management was higher than in wet management.

K fertilization significantly affected changes in soil K over 3 crops. K(NH_4OAc) was gradually built up from the end of the first crop (0.48-1.84 mmol kg^{-1}) to the end of the third crop (2.0-4.30 mmol kg^{-1}) in fertilized soils, whereas in unfertilized soils, K(NH_4OAc) was depleted even after the first crop. In general, K(NH_4OAc) at the end of the first, second and third crops decreased to a minimum level of about 0.4 mmol K kg^{-1} in CLRRI and Binh Phu clay soils and about 0.2 mmol kg^{-1} for Cau Ke loamy soil and An Cu sandy soil (Table 5.7). These minimum K values were higher for clay soils than for loamy and sandy soils. The minimum value for CLRRI and Binh Phu clay soils corresponds to the minimum value of 0.43 mmol kg^{-1} found for clay soils in Chapter 3. K(NaTPB) increased at the end of Crop 3 in fertilized soils, but not as much as K(NH_4OAc). In unfertilized soils, K(NaTPB) remained almost the same during the 3 crops cycles.

Since water management did not significantly affect K(NH_4OAc) and K(NaTPB), the values of K(NH_4OAc) and K(NaTPB) averaged over the two water management treatments will be used for further discussion on soil K changes over time under fertilized and unfertilized conditions in different soil types. As said, all soils were at the minimum value of K(NH_4OAc) in unfertilized soils at the end of Crops 1, 2 and 3 (Table 5.8). In fertilized soils, increase in K(NH_4OAc) at the end of Crop 3 was highest for Binh Phu soil. This soil with kaolinite as dominant clay mineral had a low maximum for fastening and a rather high maximum for K adsorption (Chapter 4). In Cau Ke and An Cu soils, which are low in K adsorption and fastening, K(NH_4OAc) was not much increased at the end of Crop 3.

Table 5.7: K(NH_4OAc) and K(NaTPB) (mmol kg^{-1}), as affected by water management (W), fertiliser application (K) and soils (S). Probability levels of F test were 5% (*) and 1% (**) for each factor. LSD 5% is for comparison between WxKxS means.

		K(NH_4OAc)						K(NaTPB)	
Fertiliser	Soil	Crop 1		Crop 2		Crop 3		Crop 1	Crop 3
		Begin	End	Begin	End	Begin	End	Begin	End
Wet management									
0K	CLRRI-NP	1.55	0.61	0.32	0.32	0.85	0.44	9.51	9.50
	Binh Phu	1.28	0.20	0.51	0.45	0.74	0.38	5.85	5.10
	Cau Ke	0.89	0.35	0.20	0.33	0.58	0.27	4.18	3.80
	An Cu	0.71	0.25	0.13	0.35	0.29	0.13	2.59	1.23
	Mean 0K	*1.11*	*0.35*	*0.29*	*0.36*	*0.62*	*0.31*	*5.53*	*4.91*
+K	CLRRI-NP	1.55	0.76	0.82	1.30	1.70	2.24	9.51	10.83
	Binh Phu	1.28	1.84	1.82	3.49	3.77	3.83	5.85	8.23
	Cau Ke	0.89	0.65	0.59	1.48	1.74	2.91	4.18	6.73
	An Cu	0.71	0.69	0.49	1.36	1.43	2.61	2.59	2.53
	Mean +K	*1.11*	*0.99*	*0.93*	*1.91*	*2.16*	*2.90*	*5.53*	*7.08*
Mean (wet)		**1.11**	**0.67**	**0.61**	**1.14**	**1.39**	**1.60**	**5.53**	**5.99**
Dry management									
0K	CLRRI-NP	1.55	0.65	0.39	0.47	0.83	0.40	9.51	9.57
	Binh Phu	1.28	0.27	0.50	0.56	1.10	0.39	5.85	5.63
	Cau Ke	0.89	0.38	0.20	0.30	0.66	0.34	4.18	4.00
	An Cu	0.71	0.23	0.20	0.31	0.35	0.15	2.59	1.37
	Mean 0K	*1.11*	*0.38*	*0.32*	*0.41*	*0.74*	*0.32*	*5.53*	*5.14*
+K	CLRRI-NP	1.55	0.73	0.71	1.41	1.54	2.00	9.51	9.97
	Binh Phu	1.28	1.60	1.58	3.72	4.14	4.30	5.85	9.67
	Cau Ke	0.89	0.56	0.70	1.91	2.42	2.53	4.18	6.20
	An Cu	0.71	0.48	0.63	1.51	3.64	2.96	2.59	3.10
Mean+ K		*1.11*	*0.84*	*0.91*	*2.14*	*2.94*	*2.95*	*5.53*	*7.24*
Mean (dry)		**1.11**	**0.61**	**0.61**	**1.27**	**1.84**	**1.63**	**5.53**	**6.19**
F test (W)		-	ns	ns	ns	ns	ns	-	ns
F test (K)		-	**	**	**	**	**	-	**
F test (S)		-	**	**	**	**	**	-	**
LSD 5% (W*K*S mean)		-	0.19	0.30	0.43	0.80	0.90	-	0.99

Table 5.8: Average K(NH_4OAc) (mmol kg^{-1} soil). Average results of two water management treatments for fertilized and unfertilized soils at the beginning and at the end after 3 crops.

Fertiliser	Soil	K(NH_4OAc)					
		Crop 1		Crop 2		Crop 3	
		Begin	End	Begin	End	Begin	End
0K	CLRRI-NP	1.55	0.63	0.36	0.40	0.84	0.42
	Binh Phu	1.28	0.24	0.51	0.51	0.92	0.39
	Cau Ke	0.89	0.37	0.20	0.32	0.62	0.31
	An Cu	0.71	0.24	0.17	0.33	0.32	0.14
	Average 0K	*1.11*	*0.37*	*0.31*	*0.39*	*0.68*	*0.32*
+K	CLRRI-NP	-	0.75	0.77	1.36	1.62	2.12
	Binh Phu	-	1.72	1.70	3.61	3.96	4.07
	Cau Ke	-	0.61	0.65	1.70	2.08	2.72
	An Cu	-	0.59	0.56	1.44	2.54	2.79
	Average +K	-	*0.92*	*0.92*	*2.03*	*2.55*	*2.93*

K(NaTPB) was increased at the end of Crop 3 in fertilized soils (Table 5.9). Intermediate K (IK) calculated by the difference between K(NaTPB) and K(NH_4OAc), was increased in unfertilized but not in fertilized soils. These outcomes are puzzling and seem very unlikely.

5.3.3. Calculated K flows

Table 5.10 gives the results of the calculations made with the equations of Table 5.1. For the unfertilised soils, the parallel model suggests that between 0.57 and 1.13 mmol of K was supplied by the labile pool and between 1.26 and 1.75 mmol K per kg soil by the stable pool. A strange result is the negative uptake from the intermediate pool (U_I) in three soils according to the Parallel Model. The series model suggests that there was a net flow of 0.04 to 1.78 mmol K from the stable to the intermediate pools and a net flow of 0.36 to 0.74 mmol per kg soil from the intermediate to the labile pools. So the flows of K leaving the intermediate pool are

Table 5.9: Total K, average K(NaTPB) and IK (mmol kg^{-1} soil). Average results of two water management treatments for fertilized and unfertilized soils at the beginning and at the end after 3 crops.

		K(total)	K(NaTPB)	IK	K(NaTPB)	IK
Fertiliser	Soil		Crop 1, begin		Crop 3, end	
0K	CLRRI-NP	429.23	9.51	7.96	9.54	9.12
	Binh Phu	236.92	5.85	4.57	5.37	4.98
	Cau Ke	300.00	4.18	3.29	3.90	3.60
	An Cu	224.87	2.59	1.88	1.30	1.16
	Average 0K	*297.76*	*5.53*	*4.43*	*5.03*	*4.72*
+K	CLRRI-NP	-	-	-	10.4	8.28
	Binh Phu	-	-	-	8.95	4.89
	Cau Ke	-	-	-	6.47	3.75
	An Cu	-	-	-	2.82	0.03
	Average +K	-	-	-	*7.16*	*4.24*

smaller than the flows entering the intermediate pool. This seems unlikely. Both anomalies are caused by the fact that IK_e was larger than $IK_{b.}$ We believe that one of the reasons for these anomalies is the low precision of the 0.2 M NaTPB 5 min extraction procedure. Slight changes in the extraction conditions apparently have significant affects on the amount of K extracted. The risks involved in the chosen procedure of the analysis of K(NaTPB) are large.

For the fertilised soils, striking observations are the negative values of U_{Sf} in the Parallel Model and of FSI-FIS in the Series Model. They suggest immobilization of fertiliser K in the stable pools (SK) during the pot experiment. Considering the fact that SK_e is calculated as TKb+ Fertiliser K-K(NaTPB)–U_f, and that U_f refers to the above-ground plant parts, it is possible that the calculated increase in SK is the result of neglecting the uptake of fertiliser K in roots. The increase in K(NaTPB) for LK and IK pools at the end of the experiment may also be partly attributed to K in roots.

The differences between the fertilised and unfertilised experimental treatments allowed the calculation of the apparent fate of fertiliser K (Table 5.11). On average, 60% was recovered in the above ground parts of the crops and 17% in LK. The values for IK of –3% probably must be interpreted as zero, while the fertiliser K allocated to the stable pool (26%) is likely present in the roots in the soil, at least for a substantial part.

Table 5.10: Basic experimental input data, and calculated flows of K according to the Parallel and the Series conceptual model. All data refer to three crops. Pools are in mmol kg^{-1}, and flows in mmol kg^{-1} per 95 days. For explanation see Table 5.1 and text.

	Soils			
	CLRRI-NP	Binh Phu	Cau Ke	An Cu
No K addition				
Input data		*Both models*		
Uptake	1.75	1.255	1.315	1.315
TK_b	429.23	236.92	300.00	224.87
LK_b	1.55	1.28	0.89	0.71
IK_b	7.96	4.57	3.29	1.88
SK_b	419.72	231.07	295.82	222.28
TK_e	427.48	235.67	298.69	223.56
LK_e	0.42	0.39	0.31	0.14
IK_e	9.11	4.97	3.59	1.17
SK_e	417.94	230.30	294.79	222.24
Flows		*Parallel*		
U_L	1.13	0.90	0.59	0.57
U_I	-1.15	-0.40	-0.30	0.71
U_S	1.78	0.77	1.03	0.04
Total Uptake	1.75	1.26	1.32	1.31
		Series		
FSI - FIS	1.78	0.77	1.03	0.04
FIL – FLI	0.62	0.36	0.73	0.74
Total Uptake	1.75	1.26	1.32	1.31

	Soils			
	CLRRI-NP	Binh Phu	Cau Ke	An Cu
With K addition				
Input data		*Both model*		
K fertiliser	15.69	15.69	15.69	15.69
Uptake	11.83	9.615	11.25	10.65
TK_b	444.92	252.61	315.69	240.56
LK_b	13.32	13.0	12.66	12.48
IK_b	11.88	8.49	7.1	5.80
SK_b	419.72	231.07	295.82	222.28
TK_e	433.09	243.00	304.44	229.91
LK_e	2.12	4.07	2.72	2.79
IK_e	8.28	4.885	3.745	0.03
SKe	422.69	234.05	297.98	227.10
Flows		*Parallel*		
U_{Lf}	11.20	8.98	9.94	9.69
U_{If}	3.60	3.61	3.47	5.77
U_{Sf}	-2.97	-2.97	-2.16	-4.82
Total Uptake	11.83	9.62	11.25	10.65
		Series		
FSI - FIS	-2.97	-2.97	-2.16	-4.82
FIL – FLI	0.63	0.63	1.31	0.96
Total Uptake	11.83	9.62	11.25	10.65

5.4. Discussion and Conclusions

The wet and dry water management between crops did not show a clear effect on rice yield, K uptake and K(NH_4OAc) and K(NaTPB) in this experiment. The soil in the pot experiment was perhaps not as reducing as under field conditions commonly seen. Therefore, the suggested increase of K fixation under the wet water management could not be observed.

Table 5.11: Apparent fate of fertiliser K. All data refer to three crops.

	Soils				
	CLRRI-NP	Binh Phu	Cau Ke	An Cu	Average
	Expressed in mmol K per kg soil				
To crop	10.08	8.36	9.93	9.34	9.43
In LK	1.70	3.68	2.42	2.65	2.61
In IK	-0.83	-0.09	0.16	-1.14	-0.48
In SK	4.75	3.74	3.19	4.85	4.13
Sum	15.69	15.69	15.69	15.69	15.69
	Expressed in % of added K				
To crop	64.2	53.3	63.3	59.5	60.1
In LK	10.8	23.5	15.4	16.9	16.6
In IK	-5.3	-0.6	1.0	-7.3	-3.0
In SK	30.3	23.9	20.3	30.9	26.3
Sum	100.0	100.0	100.0	100.0	100.0

K fertilization clearly affected plant and soil K behaviour. This was to be expected, since K(NH_4OAc) was below 2 mmol kg^{-1} in all soils, which is suggested to be the critical level (e.g. Jones et al. 1982).

In unfertilized soils, K(NH_4OAc) was depleted to a minimum level already at the end of Crop 1. This resulted in very poor plant growth in the second and third crops due to K deficiency. Apparently the time between two crops was too short for the replenishment of LK by IK in this three crop cycles experiment. Mc Lean and Watson (1985) recognized that once the exchangeable K has been lowered to below a certain minimum level unique for that soil, further growth and uptake by the crop is regulated by the rate of K release from non-exchangeable K. Sufficient time for LK to be replenished from IK is therefore very important. In this experiment, IK did not replenish LK. At the end of Crop 3, IK was higher than that at beginning of Crop 1, which is unlikely. The period between crops was apparently too short in the triple rice cropping system of this experiment.

Plants grew well in all 3 crops when sufficiently supplied with fertiliser K. However in Binh Phu soil, uptake was low in the first crop, although LK at the end of Crop 1 was still high. The low K uptake was probably due to a high Fe concentration in the soil solution, since plants in this soil showed iron toxicity in the first crop and to lesser degree in the second and third crops. The cause of iron toxicity was perhaps the high content in the soil of reducible Fe, in combination with the addition of a Fe containing micronutrients solution. In the second and third crop, application of N fertiliser was lowered to prevent the susceptibility to plant diseases, because yellow dwarf disease symptom was observed in some plants in the first crop. As a result grain yield and crop uptake of treatments with fertiliser K may have been reduced by shortage of N in the second and the third crops. Labile K pool gradually increased up to the end of the third crop. Also measured LK and IK at the end of Crop 3 were increased. As suggested before, the negative values of U_{Sf}, and FSI-FIS must be related in part to K in roots remaining in the soil.

Net K(NaTPB) failed to act as the intermediate K pool in the models. The main reason is probably that only a small part of the large amount of the interlayer K is extracted in 5 min. Further, the decrease in IK due to uptake by plant was probably too small to substantially affect the quantity of interlayer K. Evidently, the chosen procedure (0.2 M NaTPB, 5 min extraction) was not precise and accurate enough to assess changes in intermediate K quantitatively. Another option for analysis of IK is extraction by 0.2 M NaTPB during 96 h as found by Cox and Joern (1997). This needs to be tested further.

Because of the inadequacy of K(NaTPB) 5 min in describing the intermediate K pool, the three-pools models could not be applied to the data of this experiment. In Chapter 6, a reduced model including only 2 pools will be discussed.

Greenhouse exhaustion experiment in some soils. Crop 1.

CHAPTER 6:

MODELLING OF K DYNAMICS IN SOILS AND K UPTAKE BY CROPS

6.1. Introduction

Many studies have been made on kinetics of K adsorption and release, using different chemical extraction methods, with the purpose to find out the best equations for describing changes of soil K over time. Also, relations between crop uptake and parameters of K release kinetics have been investigated (e.g. Goulding, 1984; Cox and Joern, 1997; Ziadi et al., 2001). However, few studies have tried to describe K uptake from various soil K pools, while considering dynamic K transfers between pools.

Selim et al. (1976) developed a mathematical model to describe K reactions and transport in soils focussing on transportation of added K through a soil profile. The transformations among the various K pools were described by first order equations. However, the values of rate coefficients of adsorption-fixation and desorption-release reactions were based on assumptions and not on experiments.

The transformations between pools in the Selim model (Fig.3.1) follow a series of processes, where K moves from one pool to the next pool. K moves from minerals to the non-exchangeable pool, and next to the exchangeable pool and finally to the soil solution. Bertsch and Thomas (1985) permit K to be released from non-exchangeable sources directly to the solution phase. It is questionable whether a model in which K flows directly from one pool to another without passing the soil solution, is realistic. Moreover, it is rather difficult to derive values of model parameters for a model with pools in series as the one by Selim. Validation and testing with experimental data for rate coefficients are needed for a realistic modelling of soil K, especially under cropping conditions.

In this study, we tried to interpret our experimental data according to two model approaches. In the first one, shown in Fig. 6.1, K flows from each of the pools to solution and to crop. It is referred to as the *parallel model* in this paper. The second model is similar to the model of Selim et al. (1976) (Figure 6.2). It is referred to as the *series model* in this paper.

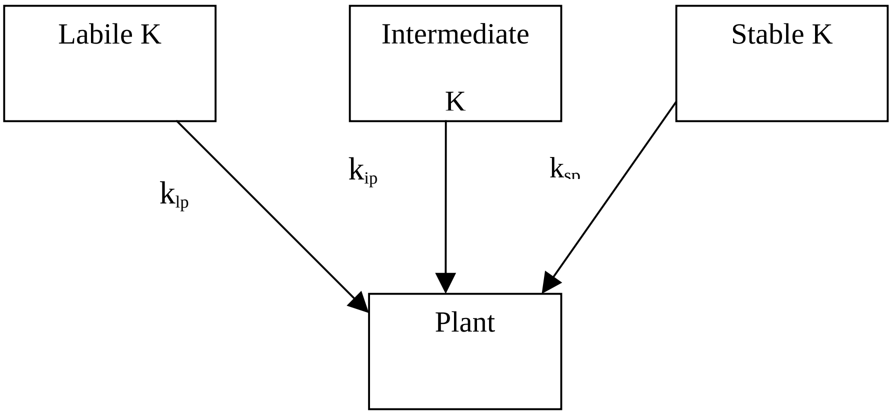


Figure 6.1: Parallel model. Flows and corresponding rate coefficients

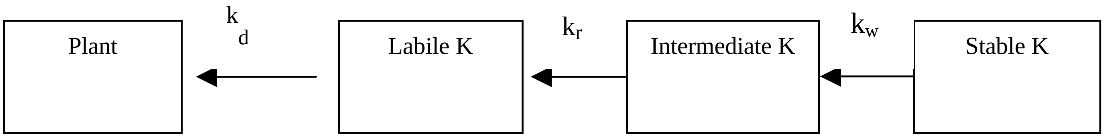


Figure 6.2: Series model. Flows and corresponding rate coefficients.

The soil K pools in the model were: labile K (LK) defined as K(NH_4OAc), intermediate K (IK) defined as the difference between K(NaTPB) and K(NH_4OAc) or 'net K(NaTPB)', and stable K (SK) defined as the difference between total K (TK) and K(NaTPB) (Table 6.1, Eq. 6.1 – 6.3). As discussed in Sections 3.3.3.1 and 3.3.3.2, the chosen extraction procedure for K(NaTPB) was 0.2 M NaTPB during 5 minutes. The transfers between pools were in first instance described by first order equations.

Two experiments were used for the calibration of model parameters: the greenhouse K exhaustion experiment described in Chapter 3 and the greenhouse K addition experiment described in Chapter 5.

The first objective of this study was to test the performance of the two conceptual models in interpreting the results of the mentioned greenhouse experiments with regard to the source of K for uptake by the plants and to the changes in soil K pools over time. The second objective was to demonstrate how the developed models can simulate the changes in soil K pools and K uptake by successive crops under field conditions.

6.2. Modelling approaches and exercises

6.2.1. General calculations

Table 6.1 presents the equations that were used for all model variants whenever applicable. The equations refer to a situation with three consecutive crops. The K uptake of each crop is measured. At the beginning of Crop 1, K(NH_4OAc), K(NaTPB) and Total K were analysed. At the end of Crop 3, again K(NH_4OAc) and K(NaTPB) were measured but not Total K. Hence the size of SK at the end of the experiment (SK_e) is calculated taking into consideration the K uptake by the crop and the decrease of LK and IK during the whole experiment (Eq. 6.7a). Equations 6.7a and 6.7b are equal, as follows from substitution of Eqs. 6.7c and 6.3 in Eq. 6.7b.

In case K(NaTPB) does not decrease over time (Section 5.3.2), it is impossible to apply a model with three K pools. In such cases only two pools of soil K were considered: labile K and a so-called recalcitrant K (RK) defined as the difference between K(total) and labile K:

$$RK \quad = K(\text{total}) - K(NH_4OAc)$$

It is discussed further in Section 6.4.

6.2.2. Parallel model

Three variants of the parallel model were distinguished. The simplest approach supposed successive exhaustion by plant uptake of one pool after another. The second variant assumed simultaneous withdrawal from the various pools. In the third variant a combination was made of successive and simultaneous withdrawal. As explained in Section 5.1, the analysis of LK does comprise exchangeable K and K in the soil solution. The uptake of K by plants takes place from the soil solution. We assumed that plants were able to take up (practically) all K present in the soil solution. Therefore in Fig 6.1 and 6.2 flows are drawn directly to plant and not to soil solution.

Variant Successive Withdrawal

In the variant successive withdrawal, it is assumed that the crop does exhaust one pool after another, to start with the labile pool LK, followed by the intermediate pool (IK), and finally the stable pool (SK). It is further assumed that the decrease of LK (DL) is caused by uptake by Crop 1. This assumption (Table 6.2, Eq. 6.8) was based on the fact that the regression coefficients of the equations relating the uptake by Crop1 to $K(NH_4OAC)$ was >1 (Tables 3.10 and 3.11). The uptake from SK by Crop 1 (USK1) is calculated as the difference between total measured K uptake by Crop 1 (U1) and the sum of DL+DI. The uptake from IK (UIK) is calculated as the difference between U1 and the sum of uptakes from the other pools (LK and SK). As a first estimation (Eq. 6.11a), uptake from IK during the second crop ($UIK2_{1st}$) is calculated by the decrease in IK (DI) corrected for uptake from IK in Crop 1 (UIK1). If $UIK2_{1st} > U2$, UIK2 is set equal to U2 (Eq. 6.11b). If $UIK2_{1st} < U2$, UIK2 is set equal to $UIK2_{1st}$ (Eq. 6.11c). Uptake from SK in

Table 6.1. Calculation of the sizes of the various K pools, and of changes in pool sizes during the greenhouse exhaustion experiment. Subscript b and e stand for the beginning and the end of the experiment.

Quantity		Equation	
Description	Code	Formula	Number
Labile	LK	$K(NH_4OAc)$	6.1
Intermediate	IK	$K(NaTPB) - K(NH_4OAc)$	6.2
Stable	SK	Total K - K(NaTPB)	6.3
Decrease of LK	DL	$LK_b – LK_e$	6.4
Decrease of IK	DI	$IK_b – IKe$	6.5
Decrease of SK	DS	$SK_b – SK_e$	6.6
SK at end	SK_e	SK_b –Uptake + DL + DI	6.7a
SK at end	SK_e	$TK_e – K(NaTPB)_e$	6.7b
Total K at end	TK_e	TK_b - Uptake	6.7c

Table 6.2. Parallel model. Variant Successive Withdrawal. Calculation of uptake by successive crops from labile, intermediate and stable K pools.

Crop	From Pool	Conditions	Code	Equation	Number
1	LK		ULK1	DL	6.8
	SK		USK1	U1 – DL – DI	6.9
	IK		UIK1	U1 – ULK1 – USK1	6.10
2	IK	First estimation	$UIK2_{1st}$	DI – UIK1	6.11a
		If $UIK2_{1st}$> U2	UIK2	U2	6.11b
		If $UIK2_{1st}$< U2	UIK2	$UIK2_{1st}$	6.11c
	SK	If $UIK2_{1st}$>U2	USK2	0	6.12a
	SK	If $UIK2_{1st}$< U2	USK2	$U2 – UIK2_{1st}$	6.12b
3	IK	If $UIK2_{1st}$> U2	UIK3	DI-UIK1-UIK2	6.13
	SK		USK3	U3 – UIK3	6.14

Crop 2 is calculated by the difference between U2 and $UIK2_{1st}$; if this difference is negative, USK2 is at at zero (Eq. 6.12a), otherwise Eq. 6.12b is used. Similarly, uptake from IK and SK in Crop 3 is calculated following Eq. 6.13 and 6.14.

Variant Simultaneous withdrawal

The second variant is based on the assumption that the plants take up K from all pools at the same time, according to first order release reactions. In principal, the reaction constant for the release from a certain Pool K is calculated from the measured sizes of Pool K at the beginning (K_b) and the end (K_b) of the experiment. Once k is known (Table 6.3, Eq. 6.15), the size of Pool K at any time (K_t) can be calculated (Eq. 6.16). Assuming that all K that is released can be and is taken up by the crop, the uptake by Crop i from a certain pool can be calculated as the difference in pool sizes between the beginning and the end of growth period i (Eqs.6.17-6.19). The reaction constants for LK, IK, and SK are denoted by k_{lp}, k_{ip} and k_{sp}, respectively, where subscript p stands for plant, and subscripts l, i and s for labile, intermediate and stable, respectively (Fig. 6.1).

Table 6.3. Parallel model. Variant Simultaneous Withdrawal. Equations for the calculation of reaction rate constant (k), pool size at time t (K_t), and uptake by Crop i from labile, intermediate and stable K pools. Subscript 1b and 3e and subscripts ib and ie stand for beginning of Crop 1 and end of Crop 3, and Crop i, respectively.

From Pool	Code		Equation	Number
	k	=	$(1/t) * \ln(K_{1b}/K_{3e})$	6.15
	K_t	=	$K_{1b} \exp(-k * t)$	6.16
LK	ULK_i	=	$LK_{ib} – LK_{ie}$	6.17
IK	UIK_i	=	$IK_{ib} – IK_{ie}$	6.18
SK	USK_i	=	$SK_{ib} – SK_{ie}$	6.19

Variant Combination of successive and simultaneous withdrawal

In this variant, it is assumed that the entire change in labile K (LK_b – LK_e) takes place during the first crop. The other pools were used simultaneously during all crops. Rate coefficients (k), pool sizes and uptake are calculated as explained in Table 6.3, but in this case, there is no uptake from LK by Crops 2 and 3.

6.2.3. Series model

The ‘series model’ depicted in Fig. 6.2 requires similar input data as the parallel model approach, but the three soil K pools should be measured before and after each crop. However, when soil pools are measured only at the beginning and the end of the experiment, it is still possible to find of values of k_d, k_r, and k_w in unfertilised soils.

Unfertilised soils

In unfertilised soils, only the processes directed to the soil solution are considered. The calculation of k_w is straightforward once the values of SK_b and SK_e are known:

$$dSK/dt = - k_w * SK \qquad \text{Eq. 6.20}$$

After integration:

$$SK_e = SK_b * \exp(- k_w * t) \qquad \text{Eq. 6.21}$$

$$k_w = (1/t) * \ln(SK_b/SK_e) \qquad \text{Eq. 6.22}$$

The calculation of k_d and k_r is more complicated. The labile and intermediate pools are submitted to two processes: they loose K to the next labile pool and they receive K from the next stable pool. The formulas are described from Edwards and Penney (2000) and are given in Annex 6.1.

For IK it holds:

$$dIK/dt = k_w * SK – k_r * IK \qquad \text{Eq. 6.23}$$

After substitution of SK by Eq. 6.21, integration and reorganisation:

$$IK_t = \{IK_b + (SK_b * k_w)/(k_w-k_r)\} * \exp(- k_r * t) - \{(SK_b * k_w)/(k_w-k_r)\} * \exp(- k_w * t) \qquad \text{Eq. 6.24}$$

After solution of k_w with Eq. 6.22, k_r is the only unknown in Eq. 6.24, and can be solved.

For LK it holds:

$$dLK/dt = k_r * IK – k_d * LK \qquad \text{Eq. 6.25}$$

After substitution of IK by Eq. 6.24, integration and reorganisation:

$$LK_t = [LK_b – \{(SK_b * k_w * k_r)/(k_w-k_r)*(k_w-k_d)\} + \{ k_r/(k_r-k_d)\}* \{IK_b + (SK_b * k_w)/(k_w-k_r)\}] * \exp(- k_d* t) - \{ k_r/(k_r-k_d)\}* \{IK_b + (SK_b * k_w)/(k_w-k_r)\} * \exp(- k_r* t) - [(SK_b * k_w * k_r)/\{(k_w-k_d)* (k_w-k_r)\}] * \exp(- k_w * t) \qquad \text{Eq. 6.26}$$

After solution of k_r with Eq. 6.24, k_d is the only unknown in Eq. 6.26, and can be solved.

For the calculation of the uptake of K, the difference between LKb and LKe is taken into account as well as the flows from SK to IK and from IK to LK. This was explained in Section 5.2.2 and is calculated with Eq. 5.13b, Table 5.1.

Fertilised soils

In fertilised conditions, the rate coefficients were calculated for each crop separately. Further it was assumed that fertiliser K dissolves immediately after application and that the subsequent adsorption to the labile pool and fixation in the intermediate pool are instantaneous processes in the proportion of 75:25. This proportion is derived from the average ratio of K_{max}-K_0 for adsorption to K_{max}-K_0 for fastening in Table 4.1. Therefore LK and IK in fertilised soil at the beginning of a crop (LK_{bf} and IK_{bf}) are calculated by adding parts of fertiliser K (F) to LK and IK:

$$LK_{bf} = LK_b + 0.75\ F \qquad \text{Eq. 6.27}$$

$$IK_{bf} = IK_b + 0.25\ F \qquad \text{Eq. 6.28}$$

6.3. Experiments for model calibration

Greenhouse K exhaustion experiment

The greenhouse experiment with 19 soils described in Chapter 3 was used for studying the withdrawal of K from the various pools by rice plants during 3 successive crop-periods of 5 weeks each. The uptake of K was measured for each crop, and K(NH_4OAc) and K(NaTPB) at the beginning of Crop1 and at the end of Crop 3.

Greenhouse K addition experiment

The greenhouse K addition experiment with three full 95 days crop cycles described in Chapter 5 was used to study soil K changes under fertilized and unfertilized conditions. The uptake of K was determined for each crop, K(NH_4OAc) at the beginning and at the end of each crop, and K(NaTPB) at the beginning of the first crop and at the harvest of the third crop. Original Total K values (Table 3.7) were used as Total K at beginning of the first crop (TK_b). Since water management had no effect on uptake, K(NH_4OAc) and K(NaTPB), the average values of these characteristics in the wet and dry treatments were used in the model calculations.

6.4. Results

6.4.1. Greenhouse K exhaustion experiment

6.4.1.1 Parallel model

Variant Successive Withdrawal

Input data are shown in Table 6.4 and results of the calculations of the various fluxes are shown in Table 6.5. Some major observations are:

DL was (slightly) negative in Soils 14, 15 and 16 and the uptake from LK by Crop 1 (ULK1) was set at 0 for these soils. It was indicated in Chapter 3 that the texture of these soils was silty clay loam (Table 3.3), and that the ratio K(NH_4OAc)/ K(NaTPB) was lower than in the other soils. It is possible that K(NaTPB) could replenish K(NH_4OAc) at such a rate that the original level of K(NH_4OAc) could be maintained. Another explanation is that the relative K saturation was already at the minimum level (0.7% of CEC, Table 3.4). Also in the other soils with low relative K saturation, DL was low (Soils 7, 8, 9, 10, 11 and 13).

The soils may be distinguished in 4 groups on the basis of the degree of exhaustion (Table 6.6). Only on three soils (Soil 2, 10 and 18), the uptake by Crop 1(U1) exceeded the sum of DL and DI, implying that already during the first crop, SK was addressed. In these soils UIK2 and UIK3 were zero and SK supplied all K for uptake by Crops 2 and 3. Soil 18 is a sandy soil in which K is mainly in the form of labile K and mineral K, and K(NaTPB) is very poor (Table 3.7); therefore, it is to be expected that all labile and intermediate K is rapidly exhausted. Soil 2 had the highest uptake of all soils, and apparently already the first crop needed to use K from SK. Soil 10 was low in K(NH_4OAc) and SK was exploited only a little during Crop 1. The ratio K($CaCl_2$)/K(NH_4OAc) decreased from Class 1 to Class 4 (Table 6.6). The ratio K(NH_4OAc)/ K(NaTPB) was higher in the easily exhausted soils (Class 1) than in the soils of Classes 2 and 3. The silt content was relatively low in soils of Class 1, and relatively high in soils of Classes 2 and 3. Soils of Class 4 behaved somewhat differently; these old alluvial soils had kaolinite as clay mineral and the others had illite; moreover Soils 12 and 13 had received more fertiliser K than the other soils (Table 3.2). From Table 6.6, it follows that the ratio K($CaCl_2$/K(NH_4OAc) seems the best indicator for the speed of exhaustion of available K: the higher the ratio the sooner the soil is exhausted.

Table 6.4: Greenhouse exhaustion experiment. Input data derived from Chapter 3.

Soil	LK_b	LK_e	IK_b	IKe	SK_b	U1	U2	U3	U1+U2+U3
1. Cang long	4.34	1.72	11.81	8.84	482.07	2.73	2.01	1.16	5.90
2. Tan An	4.03	1.91	16.01	12.26	442.27	6.78	2.51	1.28	10.58
3. Cho Moi	3.64	1.09	13.95	8.59	570.10	5.66	1.54	1.09	8.29
4. Chau Thanh KG	3.42	1.64	15.10	9.78	346.10	4.20	2.42	1.25	7.87
5. Cai Lay	2.69	1.29	12.97	8.20	461.01	4.88	2.69	0.68	8.24
6. Chau Phu	1.84	1.05	11.96	8.04	541.84	3.54	1.92	1.05	6.51
7. CLRRI- NP	1.55	1.40	7.97	4.77	419.72	2.61	1.04	0.94	4.59
8. 2 CLRRI- NPK	1.74	1.57	8.03	6.36	444.08	2.15	1.01	0.96	4.11
9. 2 CLRRI- NP	1.69	1.25	6.96	5.35	424.94	1.33	0.97	0.80	3.10
10. Thoai son	1.39	1.13	11.95	10.35	447.17	2.00	1.53	0.92	4.46
11. Vinh Trinh	1.22	0.76	10.98	9.88	486.01	0.98	1.00	0.78	2.76
12. Binh Phu MH	1.28	0.85	4.57	2.35	231.07	1.04	0.34	0.42	1.80
13. Vinh Hung MH	1.00	0.88	3.86	2.45	348.47	0.65	0.17	0.32	1.14
14. Tan Chau Trang	1.06	1.11	11.48	8.73	534.64	1.58	0.67	0.72	2.98
15. Tan Chau Bon	1.03	1.24	13.93	11.49	545.04	1.17	0.86	0.84	2.87
16. Tan Chau Tho	0.85	1.17	11.86	9.75	494.22	0.81	0.81	0.94	2.56
17. Cau Ke	0.89	0.81	3.30	2.24	295.82	0.97	0.36	0.38	1.72
18. An Cu	0.71	0.31	1.88	1.75	222.28	1.09	0.18	0.23	1.50
19. Go Tranh	0.52	0.38	2.30	1.87	66.15	0.35	0.18	0.19	0.73

Table 6.5. Greenhouse exhaustion experiment. Parallel model. Variant Successive withdrawal. Stepwise calculation of K uptake from different K pools. For explanation see text and Equations 6.4-6.14 in Table 6.1 and 6.2.

	Equation	6.4	6.5	6.8	6.9	6.10	6.11abc	6.12ab	6.13	6.14
Soil	Site	DL	DI	ULK1	USK1	UIK1	UIK2	USK2	IK3	USK3
1.	Cang Long -TV	2.61	2.97	2.61	nu	0.12	2.01	nu	0.83	0.33
2.	Tan An - LA	2.12	3.75	2.12	0.915	3.75	nu	2.51	nu	1.28
3.	Cho Moi - AG	2.55	5.36	2.55	nu	3.11	1.54	nu	0.71	0.38
4.	Chau Thanh - KG	1.77	5.32	1.77	nu	2.42	2.42	nu	0.48	0.77
5.	Cai Lay - TG	1.16	5.01	1.40	nu	3.48	1.29	1.40	nu	0.68
6.	Chau Phu - AG	0.80	3.91	0.79	nu	2.75	1.17	0.75	nu	1.05
7.	CLRRI- NP plot	0.15	3.20	1.41	nu	1.20	0.74	0.30	nu	0.94
8.	2 CLRRI – NPK plot	0.17	1.67	1.58	nu	0.57	nu	1.01	nu	0.96
9.	2 CLRRI – NP plot	0.44	1.61	0.44	nu	0.89	0.72	0.25	nu	0.80
10.	Thoai Son - AG	0.26	1.60	0.26	0.144	1.60	nu	1.53	nu	0.92
11.	Vinh Trinh -TN-CT	0.46	1.10	0.46	nu	0.52	0.58	0.42	nu	0.78
12.	Binh Phu -MH - LA	0.43	2.22	0.43	nu	0.60	0.34	nu	1.27	nu
13.	Vinh Hung-MH-LA	0.12	1.41	0.12	nu	0.53	0.17	nu	0.72	nu
14.	Tan Chau (Trang)	-0.05	2.75	nu	nu	1.58	0.67	nu	0.50	0.23
15.	Tan Chau (Bon)	-0.21	2.44	nu	nu	1.17	0.86	nu	0.41	0.43
16.	Tan Chau (Tho)	-0.33	2.11	nu	nu	0.81	0.81	nu	0.49	0.46
17.	Cau Ke - TV	0.07	1.05	0.07	nu	0.90	0.15	0.21	nu	0.38
18.	An Cu - AG	0.40	0.13	0.40	0.567	0.13	nu	0.18	nu	0.23
19.	Go Tranh-MH-LA	0.14	0.43	0.14	nu	0.22	0.18	nu	0.03	0.16

[a/] nu = no uptake from this pool by this crop.

Table 6.6. Greenhouse K exhaustion experiment. Parallel model. Variant Successive Withdrawal. Classification of soils in relation to the rate of exhaustion, denoted by the crop number during which the stable K (SK) was exploited for the first time, and class average values of some selected soil parameters.

	Exhaustion class			
	1	2	3	4
Soils	2, 10, 18	5,6,9,11,17,19	1,3,4,7,8,14, 15,16	12,13
First exploitation of SK by	Crop1	Crop 2	Crop 3	None
K($CaCl_2$)/(K(NH_4OAc)	0.45	0.37	0.33	0.15
K(NH_4OAc)/(K(NaTPB)	0.19	0.17	0.15	0.21
Silt, %	31	37	47	39
K(NH_4Oac)$_{end}$/CEC, %	1.36	0.94	0.92	0.92
K(NH_4Oac)$_{end}$/K(NH_4OAc)$_{begin}$, %	57	68	83	77
K(NaTPB)$_{end}$/ K(NaTPB)$_{begin}$, %	79	74	72	62

Variant Simultaneous Withdrawal

Rate coefficients (k_{lp}, k_{ip} and k_{sp}) calculated with Eq. 6.15 are shown in Table 6.7 and the calculated uptake from the various pools during the three crops in Table 6.8. Comparison between calculated and measured uptake showed that the calculation underestimated U1 and overestimated U3 (Fig.6.3). The interpretation is that under the intensive cropping conditions of this greenhouse experiment, LK is exhausted in a shorter period than IK and SK. It is therefore to be expected that an increase of k_{lp} would result in an increase of calculated U1.

Variant Combination of Successive and Simultaneous Withdrawal

In this variant, the decrease in LK was supposed to be completed in the first crop, and therefore k_{lp} was about three times as high as in the variant of simultaneous withdrawal, while k_{im} and k_{sm} kept the same values (Table 6.7). As a result calculated U1 from LK increased, and also calculated total U1. Because uptake from LK was set at zero for Crops 2 and 3, total uptake during Crops 2 and 3 decreased (Table 6.9). The calculated uptakes in this variant approached the measured uptake better (Fig. 6.4) than those in the simultaneous variant. This suggests that under strong exhaustion LK is indeed exhausted in a short time, and later uptake is depending on the other pools, IK and SK.

6.4.1.2. Series model

The Series model was tested for some selected soils only (Soil 2, 6 and 10) representing the 3 groups which were high, at equilibrium and low in the relation between K(NH_4OAc) and K(NaTPB) as discussed in Chapter 3 (Fig 3.5). Input data on pool sizes and uptakes during 3 crops (105 days) are shown in Table 6.10. From the input data, rate coefficients k_w, k_r and k_d were derived by Eqs. 6.22-6.26. Also SK, IK and LK at the end of each crop were calculated as well as the uptake by each crop. The uptakes calculated for Crop 1 were too low and those for Crop 3 were too high. The uptakes calculated for Crop 2 were too high for Tan An and Chau Phu, but that for Thoai Son soil was correct. The conclusion is that also for the series model, it must be assumed that the value of LK_e, measured at the end of Crop3 was reached earlier. No attempts were made to modify the model accordingly.

6.4.2. Greenhouse K addition experiment

Because K(NaTPB) and IK did not decrease in this experiment (Section 5.3.2), the models were tested with only two pools: labile K (LK) and recalcitrant K (RK).

Table 6.7. Greenhouse exhaustion experiment. Parallel model. Rate coefficients (*1000) for different pools in Variant Simultaneous Withdrawal and of LK in Variant Combination of successive and simultaneous withdrawal of K. The numbers added to k_{lp} refer to the time interval (in days) that was required to exhaust LK. See text.

Soil No.	Soil	Simultaneous exhaustion			Combination
		Labile pool	Intermediate pool	Stable pool	Labile pool
		k_{lp100}	k_{ip}	k_{sp}	k_{lp35}
1.	Cang Long	8.78	2.76	0.01	26.34
2.	Tan An	7.13	2.54	0.10	21.38
3.	Cho Moi	11.49	4.62	0.01	34.46
4.	Chau Thanh KG	6.98	4.14	0.02	20.94
5.	Cai Lay	7.00	4.36	0.04	20.99
6.	Chau Phu	5.34	3.78	0.03	16.01
7.	CLRRI- NP	0.94	4.89	0.03	2.82
8.	2CLRRI- NPK	0.98	2.22	0.05	2.94
9.	2CLRRI- NP	2.87	2.50	0.02	8.61
10.	Thoai son	1.95	1.37	0.06	5.84
11.	Vinh Trinh	4.51	1.00	0.02	13.52
12.	Binh Phu MH	3.94	6.32	0.00	11.82
13.	Vinh Hung MH	1.21	4.35	0.00	3.63
14.	Tan Chau Trang	0.00	2.61	0.00	0.00
15.	Tan Chau Bon	0.00	1.83	0.01	0.00
16.	Tan Chau Tho	0.00	1.86	0.02	0.00
17.	Cau Ke	0.79	3.67	0.02	2.36
18.	An Cu	7.91	0.66	0.04	23.72
19.	Go Tranh	2.87	1.96	0.02	8.60

Table 6.8: Greenhouse exhaustion experiment. Parallel model. Variant Simultaneous Withdrawal. Calculated uptake from LK, IK and SK during Crop 1, Crop 2 and Crop 3.

	Soil	Crop 1				Crop 2				Crop 3			
		LK	IK	SK	Total	LK	IK	SK	Total	LK	IK	SK	Total
1.	Cang long	1.15	1.09	0.11	2.34	0.84	0.99	0.11	1.94	0.62	0.90	0.11	1.62
2.	Tan An	0.89	1.36	1.57	3.83	0.69	1.25	1.57	3.51	0.54	1.14	1.56	3.24
3.	Cho Moi	1.21	2.08	0.13	3.41	0.81	1.77	0.13	2.70	0.54	1.51	0.13	2.17
4.	Chau Thanh	0.74	2.04	0.26	3.03	0.58	1.76	0.26	2.60	0.45	1.52	0.26	2.23
5.	Cai Lay	0.58	1.84	0.69	3.11	0.46	1.58	0.69	2.73	0.36	1.35	0.69	2.40
6.	Chau Phu	0.31	1.48	0.60	2.40	0.26	1.30	0.60	2.16	0.22	1.14	0.60	1.95
7.	CLRRI- NP	0.05	1.25	0.42	1.72	0.05	1.06	0.42	1.52	0.05	0.89	0.42	1.35
8.	2CLRRI- NPK	0.06	0.60	0.76	1.42	0.06	0.55	0.76	1.37	0.05	0.51	0.76	1.32
9.	2CLRRI- NP	0.16	0.58	0.35	1.10	0.15	0.54	0.35	1.03	0.13	0.49	0.35	0.97
10.	Thoai son	0.09	0.56	0.87	1.52	0.09	0.53	0.87	1.49	0.08	0.51	0.86	1.45
11.	Vinh Trinh	0.18	0.38	0.40	0.96	0.15	0.37	0.40	0.92	0.13	0.35	0.40	0.88
12.	Binh Phu	0.16	0.91	-0.28	0.79	0.14	0.73	-0.28	0.59	0.13	0.58	-0.28	0.42
13.	Vinh Hung	0.04	0.54	-0.13	0.45	0.04	0.47	-0.13	0.37	0.04	0.40	-0.13	0.31
14.	Tan Chau Trang	-0.02	1.00	0.09	1.08	-0.02	0.92	0.09	0.99	-0.02	0.84	0.09	0.91
15.	Tan Chau Bon	-0.07	0.86	0.21	1.01	-0.07	0.81	0.21	0.95	-0.07	0.76	0.21	0.90
16.	Tan Chau Tho	-0.10	0.75	0.26	0.91	-0.11	0.70	0.26	0.85	-0.12	0.66	0.26	0.80
17.	Cau Ke	0.02	0.40	0.20	0.62	0.02	0.35	0.20	0.57	0.02	0.31	0.20	0.53
18.	An Cu	0.17	0.04	0.33	0.54	0.13	0.04	0.32	0.50	0.10	0.04	0.32	0.46
19.	Go Tranh	0.05	0.15	0.05	0.26	0.04	0.14	0.05	0.24	0.04	0.13	0.05	0.23

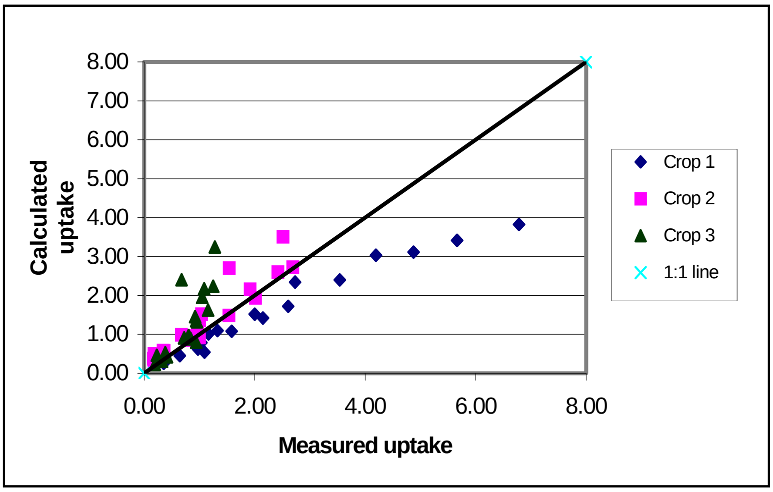


Figure 6.3: Greenhouse K exhaustion experiment. Parallel model. Variant Simultaneous Withdrawal. Comparison of calculated and measured uptake (mmol kg^{-1}).

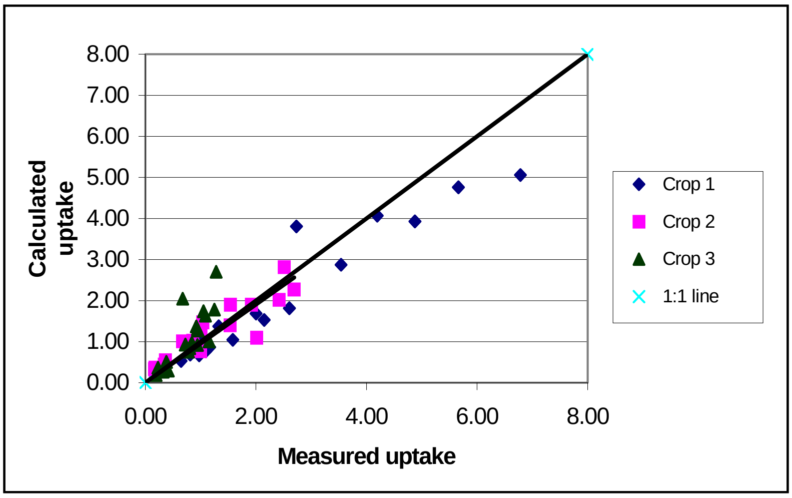


Figure 6.4: Greenhouse K exhaustion experiment. Parallel model. Variant Combination of Successive and Simultaneous Withdrawal. Comparison of calculated and measured uptake (mmol kg^{-1}).

Table 6.9: Greenhouse exhaustion experiment. Parallel model. Variant Combination Successive and Simultaneous Withdrawal. Calculated uptake from LK during Crop 1 and total uptake from LK, IK and SK during Crop 1, Crop 2 and Crop 3.

		LK	Total uptake		
		Crop 1	Crop 1	Crop 2	Crop 3
1	Cang long	2.61	3.81	1.09	1.00
2	Tan An	2.12	5.06	2.81	2.70
3	Cho Moi	2.55	4.76	1.90	1.63
4	Chau Thanh	1.77	4.07	2.02	1.78
5	Cai Lay	1.40	3.93	2.27	2.04
6	Chau Phu	0.79	2.87	1.90	1.74
7	CLRRI- NP	0.15	1.81	1.47	1.30
8	2CLRRI- NPK	0.17	1.53	1.31	1.27
9	2CLRRI- NP	0.44	1.37	0.88	0.84
10	Thoai son	0.26	1.68	1.40	1.37
11	Vinh Trinh	0.46	1.24	0.77	0.75
12	Binh Phu	0.43	1.06	0.44	0.30
13	Vinh Hung	0.12	0.53	0.34	0.27
14	Tan Chau Trang	0.00	1.10	1.01	0.93
15	Tan Chau Bon	0.00	1.08	1.02	0.97
16	Tan Chau Tho	0.00	1.01	0.96	0.92
17	Cau Ke	0.07	0.67	0.55	0.51
18	An Cu	0.40	0.77	0.37	0.37
19	Go Tranh	0.14	0.34	0.20	0.19

Table 6.10: Greenhouse exhaustion experiment. Series model for some selected soils. Input data and calculation of rate coefficients and K pools.

	Tan An	Chau Phu	Thoai Son
Input data			
TK_b	462.31	555.64	460.51
LK_b	4.03	1.84	1.39
IK_b	16.01	11.96	11.95
SK_b	442.27	541.84	447.17
LK_{e3}	1.91	1.05	1.13
IK_{e3}	12.26	8.04	10.35
SK_{e3}	437.56	540.04	444.57
U1	6.78	3.54	2.00
U2	2.51	1.92	1.53
U3	1.28	1.05	0.92
Calculated rate coefficients and K pools			
k_w*1000	0.10	0.03	0.06
k_r*1000	5.77	6.00	3.60
k_d*1000	19.69	32.00	13.58
Crop1			
LK_e	3.08	1.54	1.33
IK_e	14.51	10.39	11.35
SK_e	440.69	541.24	446.30
U1	4.03	2.47	1.53
Crop 2			
LK_e	2.40	1.27	1.24
IK_e	14.51	9.10	10.82
SK_e	439.124	540.64	445.43
U2	3.47	2.15	1.49
Crop 3			
LK_e	1.91	1.05	1.13
IK_e	12.26	8.04	10.35
SK_e	437.56	540.04	444.57
U3	3.07	1.89	1.44

6.4.2.1. Parallel model

Only the Variant Combination of successive and simultaneous withdrawal was tested, because it proved to be the most promising Variant of the Parallel Model (Section 6.4.1.1) when tested in the exhaustion experiment. The code for flows of transferring K from RK to the soil solution (in other words, the K uptake from RK) is URK, similar to the codes used in Table 5.1, and the corresponding rate coefficient is coded k_{rp}, similar to the codes used in Table 6.7.

Input data and results of k_{lp}, k_{rp} in unfertilised soils are shown in Table 6.11. For the calculation of k_{lp}, it was assumed that the change in LK (DL) took place in 95 days. In general, the calculated uptake agreed with the measured uptake in Fig. 6.5, showing that the model was able to correctly estimate the uptake by the 3 crops in this experiment.

In fertilised soils, derived k_{lp} (Table 6.12) was higher in Crop 1 than in Crop 2 because plant uptake was higher in Crop 1 than in Crop 2 and 3. The calculated of k_{rp} were highest for Crop 2. Because the rate coefficients were derived for each crop separately, the calculated uptakes were similar to measured uptake, and are not shown.

6.4.2.2. Series model

Results of the calculation of k rates for fertilised and unfertilised soils are shown in Table 6.13. Calculated and measured uptakes of unfertilised soils are compared in Fig 6.6. The fit is less good as in Fig 6.5 for the Variant Combination of successive and simultaneous withdrawal. Also for the Series, such a combination is needed, but it was not tried out. In unfertilised soil, value of k_l was low in CLRRI, higher in Binh Phu soils and highest in Cau Ke and An Cu soils. This is expected because CLRRI-NP is an illitic clay, Binh Phu a kaolinitic clay soil, and Cau Ke and An Cu are loamy and sandy soils, respectively. The values of k_d in fertilised soils decreased from Crop 1 to Crop 3. The values of k_l were of course the same as those of k_{rp} in Table 6.12.

Table 6.11: Greenhouse K addition experiment. Unfertilised soils. Parallel model. Variant Combination Successive and Simultaneous Withdrawal. Input data derived from Table 5.10. Derivation of k_{lp} from LK and of k_{rp} from RK.

	CLRRI-NP	Binh Phu	Cau Ke	An Cu
No K addition				
Input data				
Uptake	1.75	1.255	1.315	1.315
TK_b	429.23	236.92	300	224.87
LK_b	1.55	1.28	0.89	0.71
RK_b	427.68	235.64	299.11	224.16
LK_{e3}	0.42	0.39	0.31	0.14
RK_{e3}	427.06	235.28	298.38	223.42
Calculated rate coefficients				
k_{lp} *1000	14	13	11	17
k_{rp} *1000	0.004	0.005	0.007	0.01

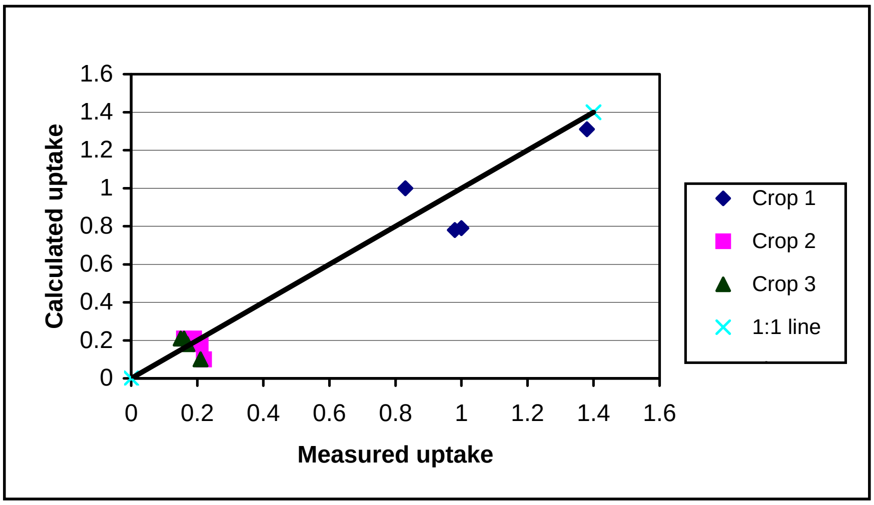


Figure 6.5: K addition Greenhouse experiment. Parallel model. Variant Combination of Successive and Simultaneous Withdrawal. Comparison of calculated and measured uptake (mmol kg^{-1}) in unfertilised soils

Table 6.12: Greenhouse K addition experiment. Fertilised soils. Parallel model. Variant Combination Successive and Simultaneous Withdrawal. Input variable and calculations are given per crops.

With K addition				
Input data				
Crop 1				
Fertilizer application	5.13	5.13	5.13	5.13
Uptake	4.77	2.86	4.715	4.28
TK_{bf}	434.36	242.05	305.13	230.00
LK_{bf}	5.40	5.13	4.74	4.56
RK_{bf}	428.96	236.93	300.39	225.44
LK_{ef}	0.76	1.71	0.63	0.57
RK_{ef}	428.84	237.48	299.79	225.15
Tk_{ef}	429.59	239.19	300.42	225.72
Crop 2				
Fertilizer application	5.19	5.19	5.19	5.19
Uptake	3.52	2.99	3.51	3.74
TK_{bf}	434.78	244.38	305.61	230.91
LK_{bf}	4.65	5.60	4.52	4.47
RK_{bf}	430.13	238.78	301.09	226.45
LK_{ef}	1.49	3.78	1.89	1.99
RK_{ef}	429.78	237.61	300.21	225.19
Tk_{ef}	431.27	241.39	302.10	227.18
Crop 3				
Fertilizer application	5.37	5.37	5.37	5.37
Uptake	3.55	3.77	3.03	2.64
TK_{bf}	436.64	246.76	307.47	232.55
LK_{bf}	5.52	7.81	5.92	6.01
RK_{bf}	431.99	241.16	302.95	228.08
LK_{ef}	2.12	4.07	2.72	2.79
RK_{ef}	430.97	238.93	301.72	227.13
Tk_{ef}	433.09	243.00	304.44	229.91
Calculated rate coefficients				
k_{rp} Crop 1*1000	0.003	-0.025	0.021	0.014
k_{rp} Crop 2*1000	0.009	0.052	0.031	0.059
k_{rp} Crop 3*1000	0.004	0.001	-0.006	-0.027
k_{lp} Crop 1*1000	20.7	11.6	21.3	21.8
k_{lp} Crop 2*1000	12.0	4.1	9.2	8.5
k_{lp} Crop 3*1000	10.1	6.9	8.2	8.1

The values for k_l and k_d of unfertilised soils in Table 6.13 were used in Eq.6.21 and 6.24 to calculate RK and LK at the end of each crop and at the beginning of the next crop, which was after 25 days fallow between two crops (Table 6.14). Calculated LK at the end of a fallow period of 25 days was higher than that at the beginning of the fallow period (Day 120 vs Day 95; Day 240 vs Day 215). This increase in LK was due to replenishment from RK during this fallow period when there was no uptake by plants. It agrees with the observations that LK pool is replenished the more, the longer the fallow period is. Whereas LK may remains low at beginning of the next crop in triple cropping systems. In triple cropping systems, replenishment of LK is not significant because the fallow period in between two crops is only about 5-7 days.

Table 6.13: Greenhouse K addition experiment. Series model. Calculated rate coefficients. Input data are the same as in Tables 6.11 and 6.12.

	CLRRI-NP	Binh Phu	Cau Ke	An Cu
No K addition				
Calculated rate coefficients				
k_l*1000	0.004	0.005	0.007	0.010
k_d*1000	6.60	5.25	8.11	12.39
With K addition				
Calculated rate coefficients				
k_l Crop 1 * 1000	0.003	-0.025	0.021	0.014
k_l Crop 2 * 1000	0.009	0.052	0.031	0.059
k_l Crop 3 * 1000	0.004	0.001	-0.006	-0.027
k_d Crop 1 * 1000	21.41	9.51	25.85	24.25
k_d Crop 2 * 1000	13.49	6.85	12.49	13.19
k_d Crop 3 * 1000	10.55	6.90	7.73	6.54

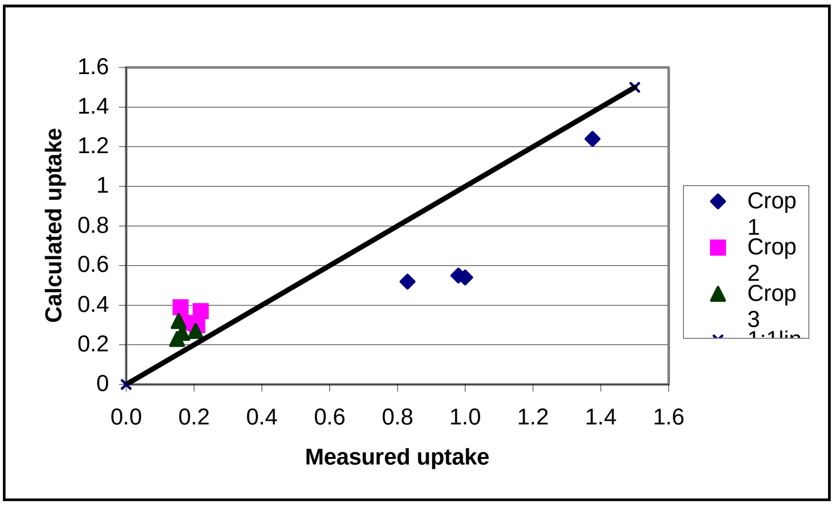


Figure 6.6: K addition Greenhouse experiment. Series model. Comparison between calculated and measured uptake (mmol kg^{-1}) in unfertilised soils.

Table 6.14: K addition experiment. Unfertilised soils. Series model. Measured and calculated LK (mmol kg^{-1}).

Day	95	120	215	240	335
Crop	Crop 1	Crop 2		Crop3	
	End	Begin	End	Begin	End
Measured LK					
CLRRI-NP	0.63	0.36	0.40	0.84	0.42
Binh Phu	0.235	0.51	0.51	0.92	0.39
Cau Ke	0.365	0.20	0.32	0.62	0.31
An Cu	0.24	0.17	0.33	0.32	0.14
Calculated LK					
CLRRI-NP	0.49	0.54	0.42	0.46	0.38
Binh Phu	0.86	0.88	0.62	0.64	0.47
Cau Ke	0.56	0.61	0.43	0.48	0.37
An Cu	0.31	0.35	0.20	0.24	0.16

6.4.3 Long-term modelling

The performance of the Parallel and Series models is demonstrated on the basis of a set of default input data, given in Table 6.15. The required input data are Total K, K(NaTPB) and K(NH_4OAc) at the beginning and at the end of one crop.

For both models, the pool sizes at the beginning and at the end of Crop 1 are calculated first, using Eqs. 6.1-6.3 of Table 6.1. Next for the Parallel model, rate coefficients k_{lp}, k_{ip}, and k_{sp} are calculated with Equation 6.15 and uptake from LK, IK and SK with Equations 6.17-6.19.

For the Series model the derivation of rate coefficients starts with k_w (Eq. 6.22), then k_r with Eq. 6.24 and finally k_d with Eq. 6.26, using pool sizes at the beginning and end of Crop 1. To solve k_r and k_d the function “goal seek” in Excel was applied. After solving the rate coefficients, the sizes of the pools at the end of Crop 2 can be calculated using Eqs. 6.21, 6.24 and 6.26 and the uptake with Eq. 5.12b, Table 5.1.

By definition, the calculated K uptake by Crop 1 is similar in both models. During the second crop, LK and IK decreased sharper in the Parallel model than in the Series model, because in the Series model LK and IK are replenished from the other pools. As a consequence, uptake is higher in the Parallel model during some years. Figure 6.7 shows the course of the three pools and the uptake during 20 years. After about 10-15 years, the uptake is about equal in the two models and depends mainly on the supply of K from the stable pool. In the parallel model, LK and IK approach zero, while in the series model, they approach equilibrium values. The latter does correspond with the measured values of LK in the K addition greenhouse experiment (Section 5.3.2). Hence we consider the Series model as the more realistic one.

6.5 Discussion and Conclusions

The Parallel model and the Series model gave the same results for crop uptake by the first crop. It implies that the total amount of K transported from soil to crop .

Table 6.15: Input data (default values) and calculated rate coefficients and uptakes of the first and second crop according to the Parallel and Series model. crop duration is 100 days. No time in between Crop 1 and Crop 2.

	Begin Crop 1	End Crop 1
Input data		
Total K	412	406
K(NaTPB)	12	8
K(NH_4OAc)	2	1
Calculated data for both models		
LK	2	1
IK	10	7
SK	400	398
Calculated data for separate models		
	Parallel	**Series**
k_{sp} *1000 and k_w*1000	0.05	0.05
k_{Ip} *1000 and k_r*1000	3.57	5.99
k_{lp} *1000 and k_d*1000	6.93	28.07
Uptake Crop 1	6.00	6.00
LK_{e2}	0.50	0.94
IK_{e2}	4.90	5.35
SK_{e2}	396.0	396
Uptake Crop 2	4.59	3.7

is the same in the first crop, irrespective whether K from the stable pools moves first to the intermediate pool and then via the labile pool to the soil solution, or from the various pools directly to the soil solution and the crop. For the following crops, K uptake slightly deviated between the two model approaches until IK and LK pools have become so small that K supply completely depends on SK. The rate of change of the pools is different for two model approaches.

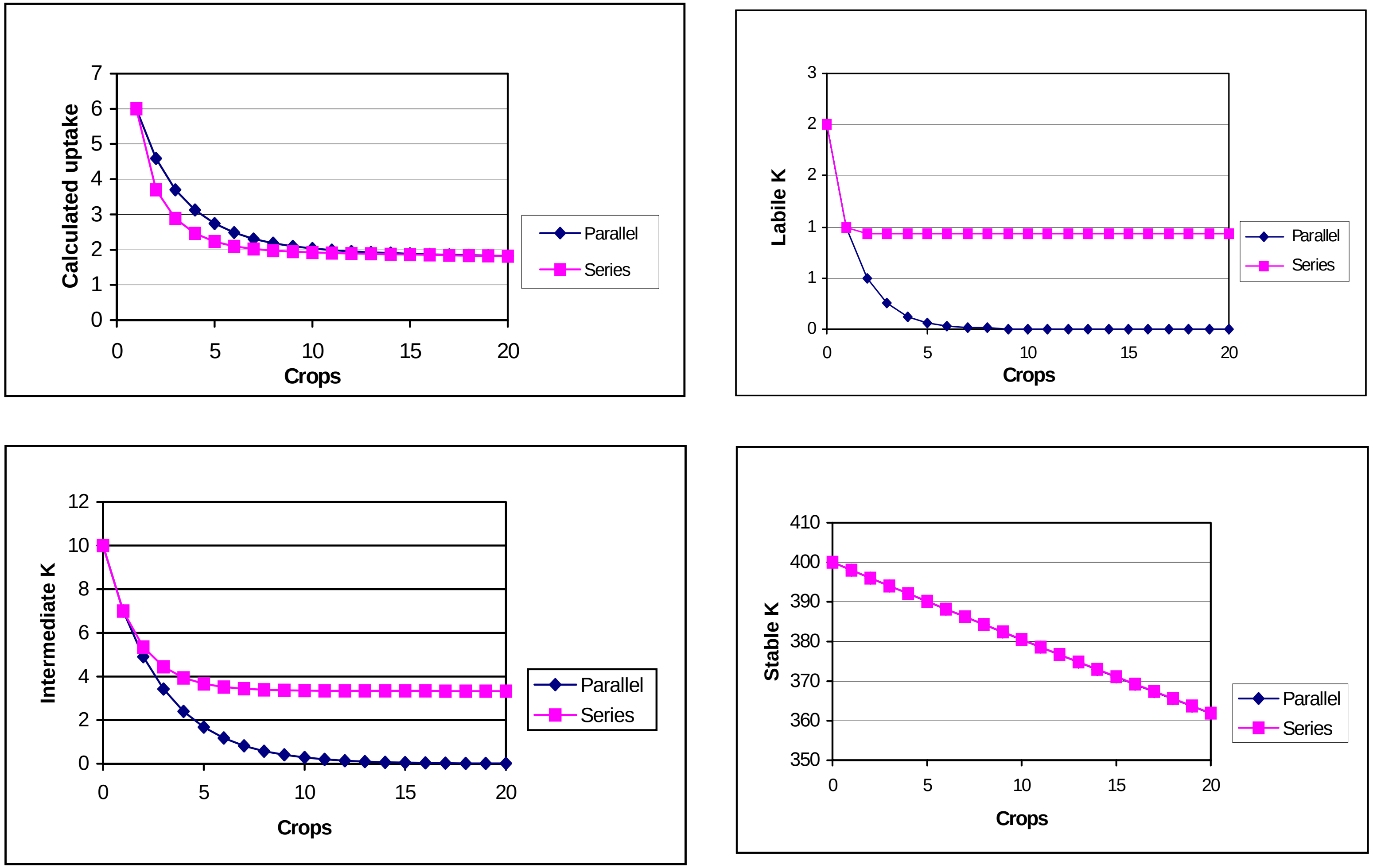


Figure 6.7: Simulated uptake (mmol kg^{-1}) and course of Labile K (LK), Intermediate K (IK) (mmol kg^{-1}) and Stable K(SK) by Parallel and Series model.

The strong point of the Parallel model is that the equations are simple, but the weak point is that it does not account for the replenishment of LK and IK, so that these pools, especially LK gets exhausted after one or more crops, which does not agree with the measured values. The strong point of the Series model is that it can account for the replenishment of IK from SK and of LK from IK. This replenishment also explains soil K recovery during fallow period between crops. The Series model explained well the K uptake and changes in soil K pools over time and allows for an understanding and predicting of soil K supply from various soil K pools. The transformation between pools was described by first order equations. The rate of reaction depends on the size of the pools. If the size of IK decreases, rate of K release decreases too. As a result LK may not be maintained at a sufficiently high level. Hence desorption of LK to solution decreases and may not meet plant demand. This can be understood and predicted from the model. The weak point of the Series model is that the calculation of soil K pools with time and the derivation of rate coefficients can not easily be solved mathematically. Further, the rate coefficients can not be easily verified experimentally.

In this study, we considered only the backward reactions. Because of the problems with the analysis of K(NaTPB) in the K addition greenhouse experiment, it was not possible to determine the rate coefficients of the forward reactions. For the time being, problems were circumvented by assuming that adsorption and fixation processes were instantaneous so that added fertiliser K could be allocated to LI and IK immediately after application.

In conclusion, the Series model as adopted from the model of Selim et al. (1976) can be used for modelling changes in soil K pools and plant K uptake overtime and it enables the prediction of soil K supply in short and long terms. The Parallel model is useful for a simple interpretation of experimental data to identify the sources of K uptake, but it is unable to predict future soil K changes and hence future K uptake.

Annex 6.1

Calculation of stable, intermediate and labile K using Eigenvalue method (Source: Edwards and Penney,2000)

The calculation of 3 K pools SK, IK and LK (stable, intermediate and labile K) was based on Eigenvalue method for homogeneous first order linear system with constant coefficients.

The system was with three pools with flow from the first to second and the third pool:

$$\begin{aligned} X'_1 &= -k_1X_1 \\ X'_2 &= k_1X_1 - k_2X_2 \\ X'_3 &= 0 + k_2X_2 - k_3X_3 \end{aligned} \qquad (1)$$

where:

$X'_i = dX_i/dt$

k_i = rate coefficients

X_i = size of the pool i

The solution vectors are of the form:

$$X(t) = \begin{bmatrix} X1 \\ X2 \\ X3 \end{bmatrix} = \begin{bmatrix}\begin{bmatrix} v_1e^{\lambda t} \\ v_2e^{\lambda t} \\ v_3e^{\lambda t} \end{bmatrix}\end{bmatrix} = \begin{bmatrix} v1 \\ v2 \\ v3 \end{bmatrix} e^{\lambda t} = ve^{\lambda t} \qquad (2)$$

where $\lambda, v1, v2, v3$ are appropriate scalar constants. For if we substitute:

$$Xi = v_i e^{\lambda t}, X'_i = \lambda v_i e^{\lambda t}$$

in (1), then the factor $e^{\lambda t}$ will cancel throughout. This will leave us with the linear equations which - for appropriate values of λ - we can solve for the values of the coefficients v_1, v_2 *and* v_3 in Eq (2) so that $X(t) = v e^{\lambda t}$, indeed, a solution of the system in (1) in the matrix form:

$$X' = AX \qquad (3)$$

where $A = [k_i]$.

When we substitute the trial solution $X(t) = V e^{\lambda t}$ with derivative $X' = \lambda ve^{\lambda t}$ in Eq (4), the result is:

(2)

$$\lambda\, v e^{\lambda t} = A\, v\, e^{\lambda t}$$

We cancel the nonzero scalar to get:

$$Av = \lambda v \qquad (4)$$

This means that $X = v\, e^{\lambda t}$ will be a nontrival solution of Eq. (3) provided that v is a *nonzero* vector and λ is a constant such that Eq.4 holds; that is, *the matrix product Av* is a scalar multiple of the vector *v*. To find *v* and λ, we rewrite Eq.4 in the form:

$$(A - \lambda I)\, v = 0$$

The number λ (either zero or nonzero) is called an eigenvalue of the *n x n* matrix A provided that $(A - \lambda I) = 0$.

And an eigenvector associated with the eigenvalue λ is a *nonzero* vector v such that AV=λ*v*, so that :

$$(A - \lambda I)\, v = 0$$

Let λ be an eigenvalue of the constant matrix A of the first order linear system:

$$\frac{dX}{dt} = AX$$

$$X'(t) = \frac{dX}{dt} = \begin{bmatrix} -k_1 & 0 & 0 \\ k_2 & -k_2 & 0 \\ 0 & k_2 & -k_3 \end{bmatrix} X$$

and vector v = [a b c] ^{T} is the associated eigenvector.

For the vector X(t) = [x_1(t) x_2(t) x_3(t)] ^{T}. The simple form of the matrix

$$A - \lambda I = \begin{bmatrix} -k_1 - \lambda & 0 & 0 \\ k_1 & -k_2 - \lambda & 0 \\ 0 & k_2 & -k_3 - \lambda \end{bmatrix} \qquad (1)$$

leads to the characteristic equation

$$\left|A-\lambda I\right| = (-k_1-\lambda)(-k_2-\lambda)(-k_3-\lambda) = 0$$

Thus the coefficient matrix A has distinct eigenvalues $\lambda_1 = -k_1, \lambda_2 = -k_2, \lambda_3 = -k_3$.

Case 1: $\lambda_1 = -k_1$. Substituting $\lambda = -k_1$ in (2), for the associated eigenvector v = [a b c]^T we get the equation :

$$A+(k1).I]v = \begin{bmatrix} 0 & 0 & 0 \\ k1 & -k2-\lambda & 0 \\ 0 & k2 & -k3-\lambda \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

The values of a, b, c are found:

$c = k_2$; $b = -(k_2-k_3)$; $a = (k_1-k_3)(k_1-k_2)/k_1$

Case 2: $\lambda_2 = -k_2$. Substituting $\lambda = -k_2$ in (2), for the associated eigenvector v = [a b c]^T we get the equation :

$$A+(k_2).I]v = \begin{bmatrix} -k1+k2 & 0 & 0 \\ k_1 & -k_2+k2 & 0 \\ 0 & k_2 & -k_3+k2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

The values of a, b, c are found:

$c = k_2$; $b = -(k_2-k_3)$; $a = 0$

Case 3: $\lambda_3 = -k_3$. Substituting $\lambda = -k_3$ in (2), for the associated eigenvector v = [a b c]^T we get the equation :

$$A+(k_2).I]v=\begin{bmatrix}-k_1+k_3 & 0 & 0\\ k_1 & -k_2+k_3 & 0\\ 0 & k_2 & -k_2+k_3\end{bmatrix}\begin{bmatrix}a\\ b\\ c\end{bmatrix}=\begin{bmatrix}0\\ 0\\ 0\end{bmatrix}$$

The values of a, b, c are found:

c = 1; a = 0; b = 0

The general solution

$$X(t) = C_1 v_1 e^{\lambda_1 t} + C_2 v_2 e^{\lambda_2 t} + C_3 v_3 e^{\lambda_3 t}$$

therefore takes the form:

$$X(t)=C_1\begin{bmatrix}\dfrac{+(k_1-k_3)(k_1-k_2)}{k_1}\\ -(k_1-k_3)\\ k_2\\ \\ \end{bmatrix}e^{-k_1 t}+C_2\begin{bmatrix}0\\ -(k_2-k_3)\\ k_2\end{bmatrix}e^{-k_2 t}+C_3\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}e^{-k_3 t}$$

C_1, C_2 and C_3 are found using boundary condition

Let t = 0; $X_1 = SK_0$; X2 = IK_0 and $X_3 = LK_0$

$$SK_0 = C_1\left(\frac{(k_1-k_3)(k_1-k_2)}{k_1}\right)+C_2.0+C_3.0$$

$$Hence \quad C_1=\frac{SK_0 k_1}{(k_1-k_3)(k_1-k_2)}$$

$$IK_0 = -\frac{SK_0 k_1}{(k_1 - k_3)(k_1 - k_2)}(k_1 - k_3) - C_2(k_2 - k_3)$$

$$C_2 = -\left[\frac{IK_0}{k_2 - k_3} + \frac{SK_0 k_1 (k_1 - k_3)}{(k_1 - k_3)(k_1 - k_2)(k_2 - k_3)}\right]$$

$$= -\frac{1}{k_2 - k_3}\left[IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right]$$

$$LK_0 = \frac{SK_0 k_1}{(k_1 - k_3)(k_1 - k_2)} k_2 - \frac{k_2}{k_2 - k_3}\left[IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right] + C_3$$

$$\textit{Hence} \quad C_3 = LK_0 - \frac{SK_0 k_1 k_2}{(k_1 - k_3)(k_1 - k_2)} + \frac{k_2}{k_2 - k_3}\left[IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right]$$

$$SK(t) = \frac{SK_0 k_1}{(k_1 - k_3)(k_1 - k_2)} \frac{(k_1 - k_3)(k_1 - k_2)}{k_1} e^{-k_1 t} = SK_0 e^{-k_1 t} \qquad \text{(=Eq.6.21)}$$

$$IK(t) = -\frac{SK_0 k_1}{(k_1 - k_3)(k_1 - k_2)}(k_1 - k_3) e^{-k_1 t} + \frac{k_2 - k_3}{k_2 - k_3}\left[IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right] e^{-k_2 t} + 0$$

$$IK(t) = \frac{-SK_0 k_1}{(k_1 - k_2)} e^{-k_1 t} + \left(IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right) e^{-k_2 t} \qquad \text{(=Eq.6.24)}$$

$$LK(t) = \frac{SK_0 k_1 k_2}{(k_1 - k_3)(k_1 - k_2)} e^{-k_1 t} - \frac{k_2}{k_2 - k_3}\left[IK_0 + \frac{SK_0 k_1}{k_1 - k_2}\right] e^{-k_2 t} +$$

$$\left\{LK_0 - \frac{SK_0 k_1 k_2}{(k_1 - k_3)(k_1 - k_2)} + \frac{k_2}{k_2 - k_3}\left[Ik_0 + \frac{SK_0 k_1}{k_1 - k_2}\right]\right\} e^{-k_3 t} \qquad \text{(=Eq. 6.26)}$$

Note that k_1, k_2 and k_3 are k_w, k_r and k_d, respectively, and SK_0, IK_0, LK_0 are SK_b, IK_b and LK_b, respectively.

Greenhouse exhaustion experiment on some soils. Crop 1.

CHAPTER 7:

GENERAL DISCUSSION AND CONCLUSIONS

7.1. Major findings of the study.

Unbalanced fertilisation with high N and P and low fertiliser K applications in intensive rice cropping systems in Asian countries has created concern about soil K depletion, and it formed the incentive for the present research. The main objectives were to get quantitative insight in K input and output budgets of intensive rice cropping systems and to acquire the knowledge on soil K dynamics needed for proper K management of intensive rice cultivation.

The major findings of the study were:

1. Partial K budgets give too negative K balances of intensive rice cultivation systems. Complete budgets are needed for a realistic judgement.
2. Especially for budgets of cropping systems with sedimentation from floods, it makes sense to differentiate between pools of increasing stability and hence of decreasing K availability.
3. A model for the interpretation and prediction of changes in soil K pools and of K uptake by crops should have at least three soil K pools, viz. a labile, an intermediate and a stable pool.
4. Extraction by 1 M NH_4OAc is suitable for the assessment of the labile K pool in soils, whereas extraction by 0.01 M $CaCl_2$ is not suitable as it does not extract sufficient K.

5. The ratio of the quantity of K extracted by 0.01 M $CaCl_2$ to the quantity of K extracted by 1 M NH_4OAc can be used as a measure of soil K depletion. The higher the ratio, the more exhausted the soil is with regard to K.

6. Although the quantities of K extracted by 0.2 M NaTPB during 5 minutes were well related to K uptake under exhaustive conditions, this NaTPB method is not suitable to monitor changes in labile plus intermediate K, because differences in the extracted quantities of K are too small in comparison to the total quantity of interlayer K. Hence, the analytical results are too sensitive to small deviations in concentration of NaTPB and in time of extraction.

7. The conversion of added fertiliser K into labile and intermediate K requires less than one day and one week, respectively.

8. Exhaustion of labile K (exchangeable K) by crops can take place within one or two months; the limiting step is plant growth and K demand, not the desorption process.

9. Release of non-exchangeable K may continue during many cropping seasons following first order kinetics, but the rate coefficient of release (k_r) decreases over time.

10. The decrease of k_r can be described with an equation of the shape: $k_r = k_{ri} * t^{-S}$, where k_{ri} stands for the initial rate coefficient of release, t is time, and S is a constant reflecting the speed of decrease of k_r.

11. The input variables for a model to predict changes in various soil K pools and K uptake over time can be derived from analyses of labile, intermediate and stable K in soil, at the beginning and the end of each of at least two cropping seasons. Assessment of K uptake by the crops is also recommended.

12. A ‘Series model’ in which K moves from the most stable pool via intermediate pools to the most labile pool and plant, gave a better description of the changes in

soil K than a ‘Parallel model’ in which K moves directly from each of the pools to the plant.

7.2. K budgeting

So far, most K balance studies are based partly on measured values and partly on assumed values of inputs and outputs. For rice cropping systems, it has often been supposed that K inputs via rainwater, irrigation water and sediments equal K losses due to percolation, runoff and erosion. In order words, a budget with chemical fertilizer as the only K input and harvested products and removed crop residues as the only K outputs would suffice. This study (Chapter 2) showed that K inputs from rainwater and irrigation water were higher than K losses due to percolation, though the net K input was relatively small, about 10 kg ha^{-1} $crop^{-1}$. Where there was sedimentation, the input of K was high, especially of K(NaTPB) and K(total), and could not be neglected in the calculation of K balances.

Rice straw removal was the largest K output in the studied systems. The return of rice straw to the field should therefore be enhanced to improve the K balance of the systems.

The differentiation between various forms of K inputs was useful for the evaluation of the K balance, and for K management. It appears that K balances based on soluble K or ammonium acetate extractable K underestimate K input into rice cropping systems, and hence result in unnecessarily alarming predictions of the future K status. The input of K in not-immediately available form could explain the absence of a response of rice to fertilizer K in areas with frequent flood and sedimentation.

7.3. Evaluation of the potassium status in the Mekong Delta

Rice cropping in the Mekong Delta is now intensified by expanding the triple crop system. Currently, farmers apply little fertiliser K as compared to fertiliser N and P. and although rice did not respond to K fertilizer at yield levels of 5-6 Mg ha^{-1} (Section 1.3.3), K mass fraction in straw was found to be low at many sites. At present, the level of K(NH_4OAc) in soil is evaluated as medium-low.

From Table 2.8 it is derived that on the average 2.5 kg K leave the field per Mg of rice grain harvested; if all straw is removed, on average 14.5 kg K is removed per Mg of grain produced. For yield of 6Mg ha^{-1} and complete straw removal, the K output is 6*(2.5+14.5) or 100 kg K is leaving the field. If K content in roots is about 20 % of total uptake, the total uptake of K is then around 120 kg K per ha or 3 kmol K or 3*10^{6} mmol K. When assuming that this amount has to be supplied by exchangeable K, and that exchangeable K cannot be exhausted to values below 0.4 mmol per kg, and that the mass of soil above the hardpan is 2*10^{6} kg, the required amount of exchangeable K can be assessed. The required amount of exchangeable K, RAEK, can be found by solving the equation: $2*10^{6} * (RAEK-0.4) = 3 * 10^{6}$. It follows that RAEK is estimated at 1.7 mmol kg^{-1}. If the volume of soil exploited by rice during one growing season is less than 100%, the value of RAEK is proportionally higher.

The calculated value of RAEK of 1.7 mmol kg $^{-1}$ approaches the critical levels found in the exhaustion experiment, which ranged from 2.1-3.2 mmol kg^{-1} for K(NH_4OAc). The critical level for K(NaTPB) ranged from 11.5 to 17.3 mmol kg^{-1}. In soils with more than 3.2 mmol kg^{-1} K(NH_4OAc) or more than 17.3 mmol kg^{-1} K(NaTPB), K desorption and release are not limiting factors of supplying K to crop. However, in soils with less than 2.1 and 11.5 mmol kg^{-1} of K(NH_4OAc) and K(NaTPB) respectively, such as in CLRRI-NP, rates of K desorption and release are low, and hence can be a limiting factor during cropping season, as was observed indeed in the low K mass fraction (about 10 g kg^{-1}) in straw in CLRRI-NP soil (Chapter 2).

Complete K budgets of double cropping systems showed that K is in balance if 35 kg ha^{-1} fertilizer K is added and rice straw is partly returned. K fertiliser may not be needed yet if all rice straw is returned to the field (Table 7.1). Our results suggest that in double cropping systems, the fallow period between two crops may be long enough for the replenishment of the labile pool from stable and intermediate pools. In triple cropping systems, the period between two crops is shorten and may be too short for the replenishment of the labile pool by the intermediate pool.

In the studied triple cropping systems, the K budget was negative for K(soluble), K(NH_4OAC) and K(NaTPB), although there was a high sediment deposition rate and rice straw was partly returned to the field (Table 7.1). Because the fallow period between two crops is short (about 5 days) in these systems, labile K was lower at the beginning of the second and the third crop than at beginning of the first crop, and hence soil K supply was lower in the second and the third season. This in combination with the higher quantities of K removed in grain and straw, it is likely the reason for the common practice of farmers to apply K fertiliser of applying of K fertiliser in triple rice cropping systems.

Table 7.1: Summary of balances (kg ha^{-1} year^{-1}) of K in various forms, in double and triple-crop systems, at specific rates of sedimentation (Mg ha^{-1} year^{-1}, dried at 40^{0}C), straw removal (kg ha^{-1} year^{-1}) and K fertiliser application (kg ha^{-1} year^{-1}). Data are derived from Chapter 2.

Cropping system	Sedimentation	Removal in straw K	Fertiliser K added	K Balance			
				Dissolved	NH_4OAc	NaTPB	Total
Double	40	79	0	-69	-66	-58	+251
	40	113	150	+44	+47	+55	+364
	94	68	70	-7	-3	+20	+1050
Triple	178	100	40	-86	-80	-48	+1125

7.4. Outline of a decision support system for K management

The knowledge acquired during this study can be brought together to develop a decision support systems for K management under intensive rice cropping systems. The framework of the decision support system (DSS) is designed in Fig 7.1. The inputs for the DSS are referring to climate, hydrology, soil and K management. The specific climatic conditions are supposed to be reflected in potential crop yield and required K by the crop. The hydrological data includes amounts of rainfall, irrigation, flooding and sedimentation, and in some areas erosion. Soil parameters include the labile, intermediate and stable K. Management comprises cropping intensity, fertiliser practice, straw management and sediment removal practice. Given the information from these inputs, the model predicts changes in soil K pools and crop uptake over time. Alternative management options can be elaborated to form a basis for recommendations on the best path to improve the system.

Details of the model are given in Fig 7.2. Inputs of K in rain, irrigation water and fertiliser are entirely or mainly allocated to LK, and K in sediments to labile, intermediate and stable K. Outputs by leaching and plant uptake are derived from LK, while erosion and sediment removal affect all three pools. K leaching may be insignificant in rice cropping systems on heavy clay soils. Straw that is incorporated in the soil can be added to the labile and intermediate pool. It may be necessary to add organic pools to the model. To start with, time steps in the model can be set equal to growth seasons and the periods between growth seasons.

7.5. Suggestions for further research

For the improvement of a decision support system on K management in rice soils in the Mekong delta, applying the developed model framework, the following research topics are suggested:

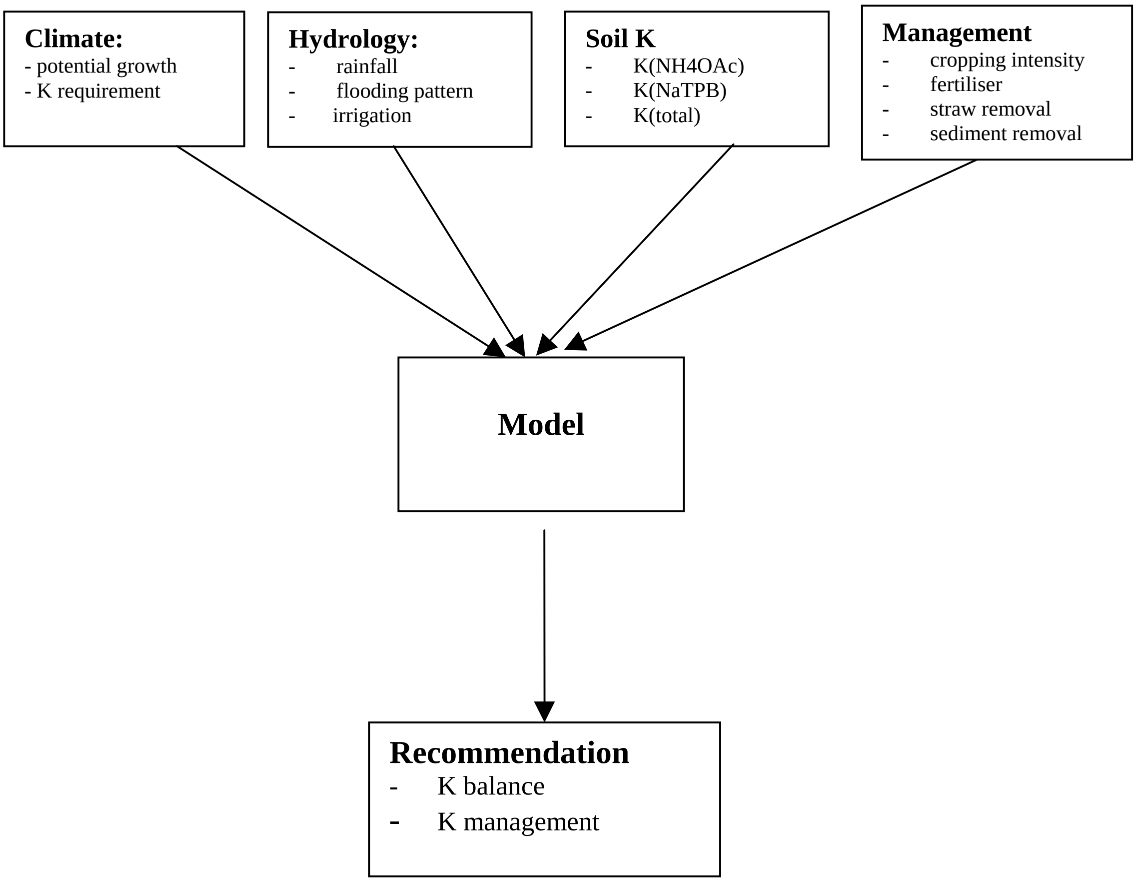


Figure 7.1: Outline for a decision support system.

Analysis of ‘ intermediate K’

Since K(NaTPB) 5 min is inadequate to describe the intermediate K pool in the three-pools model, another methods need to be developed. One option is extraction by 0.2 M NaTPB during 96 h as found by Cox and Joern (1997). This needs to be tested further.

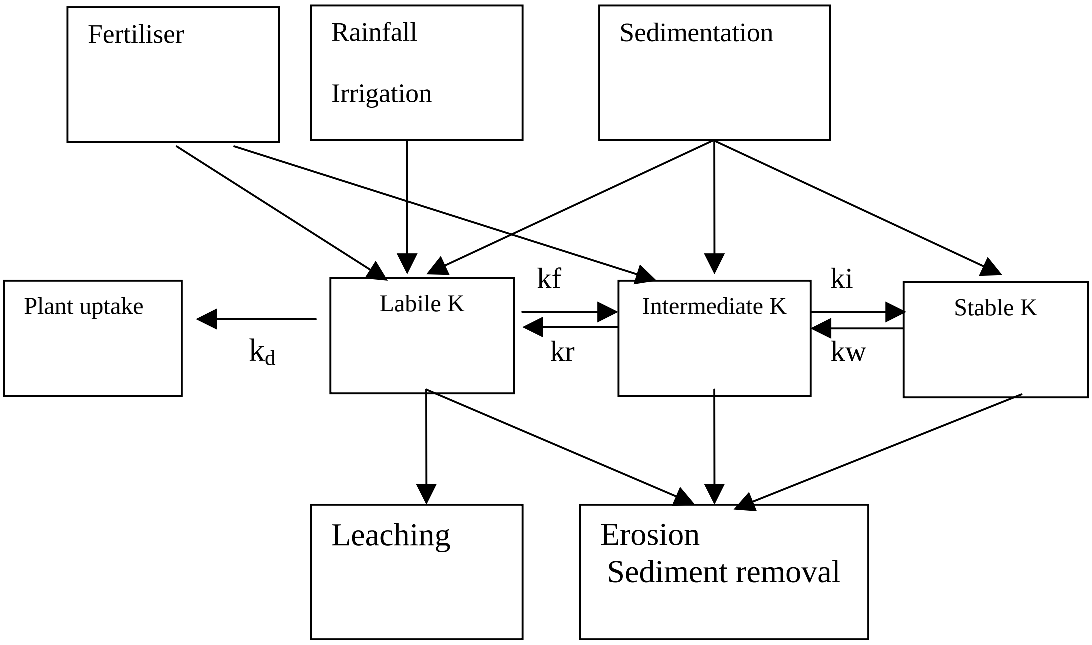


Figure 7.2. Series model including inputs-outputs and transformation between pools.

Rates coefficients under field conditions

To verify the model in field condition, rate coefficients need to be determined in field conditions as they are expected to be lower than in greenhouse experiments. Values of rate coefficients were much higher in the laboratory than in the greenhouse experiment (Table 7.2). In the greenhouse K addition experiment they were again lower than in exhaustion experiment. A preliminary estimation of k_d and k_l in the field showed, however that the values were comparable to those in the greenhouse (Table 7.2). For a proper interpretation of the model results, the rate of change of the reaction coefficients with time must be known. Inputs data needed to verify the model in field condition are the same as those discussed in Section 6.4.3. They include K uptake, labile, intermediate and stable K at beginning and at the end of each crop if a three-pools model is applied or labile K and recalcitrant K if a two-pool model is applied.

Exploring K management option

Once a suitable analysis of 'intermediate K' and appropriate rate coefficients have been found, the developed model can be applied to explore various management options and different boundary conditions, such as:

- double and triple crop systems
- with and without sedimentation
- with and without irrigation
- removal or incorporation of straw
- fertiliser K application

Mapping of areas with regard to K deficiency risk

At the beginning of our study, we prepared a map showing the risk on K deficiency in soils, based on labile K in soils (Fig 7.3) and cropping intensity in 2000 (Fig 7.4). The map is shown in Fig 7.5. The map of labile K was created on the basis of exchangeable K data collected on 136 sites on young alluvial, old alluvial, acid sulfate, and saline intruded soils in 12 provinces of the Mekong Delta. The map of double and triple rice cropping in 2000 was created by the Institute of Agricultural Planning and Projection from the land use map. The map of risky areas with regard to K deficiency is shown in Fig 7.5. Since the labile K map was not made using modern geostatistical methods, it is suggested to revise the map of K-deficiency areas. Such a revision should also be based on the simulation results from a the two-pools model discussed in Chapter 6, using all available data on labile K and estimates of total K for each soil group.

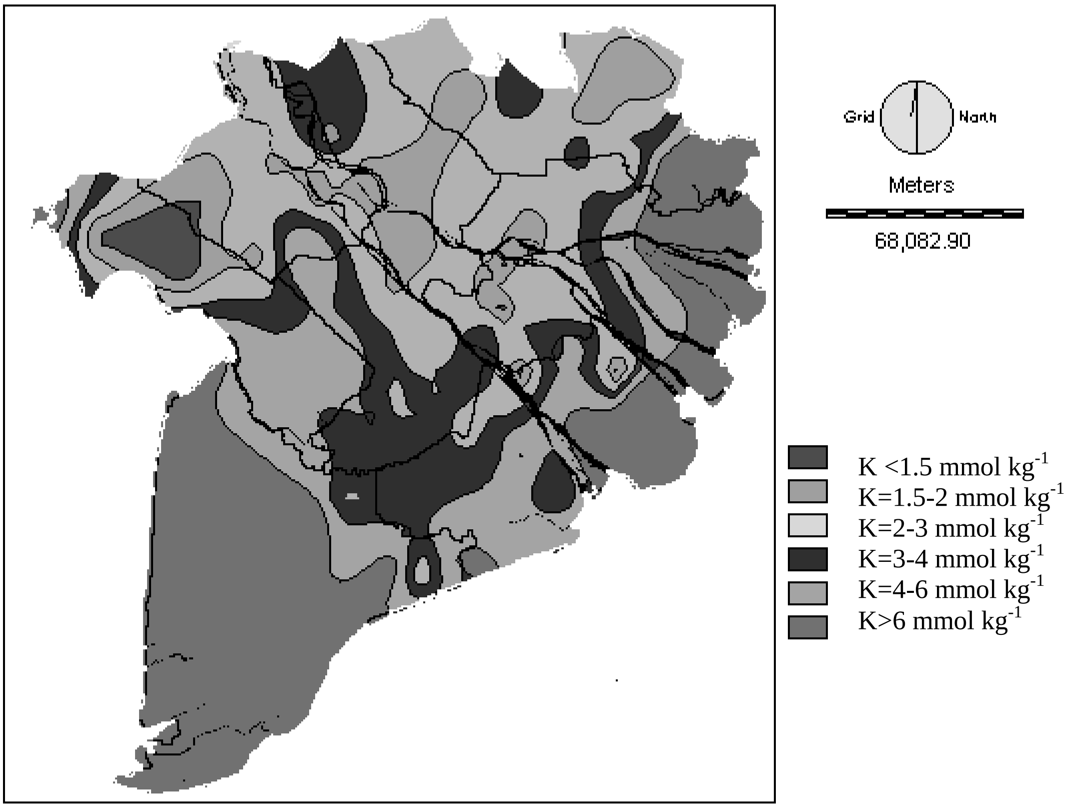


Figure 7.3: An outline of Exchangeable K map in the Mekong Delta.

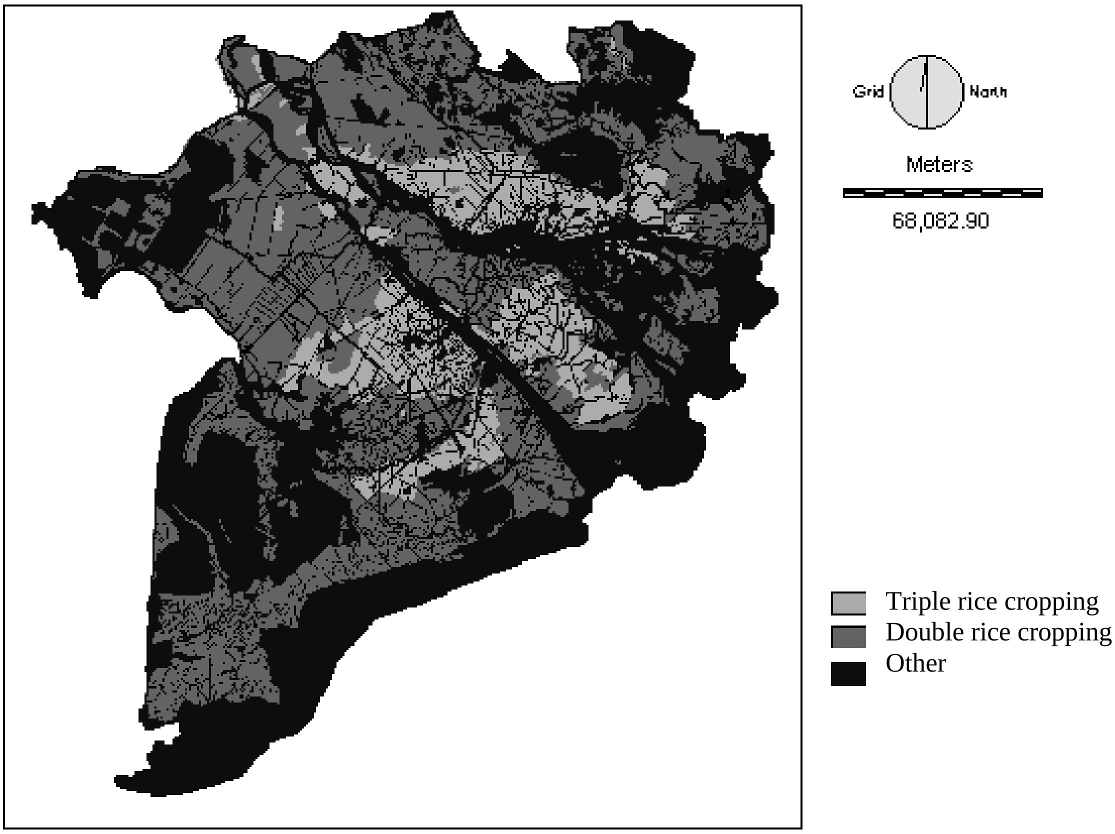


Figure 7.4: Triple and Double rice cropping area in the Mekong Delta. (Source: Institute of Agricultural Planning and Projection, 2000).

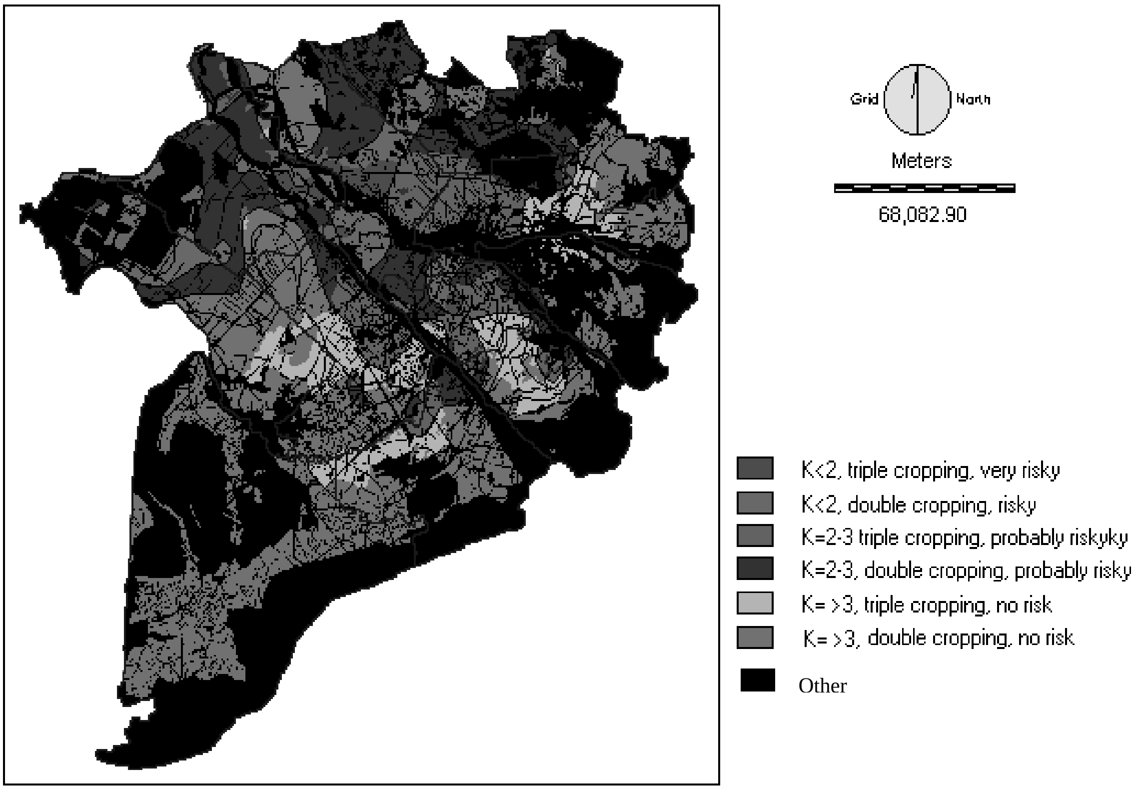


Figure 7.5: Map of combination of rice cropping intensity in 2000 and exchangeable K (mmol kg^{-1}) in the Mekong Delta.

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Summary

The Mekong Delta (MD) represents a major rice-growing region in Vietnam and also in Southeast Asia. Reports on the soil K status, soil K balance and response to fertiliser K in young alluvial rice soils in the Mekong Delta are conflicting, and recommendations for K application are inconsistent. Many fertiliser trials conducted over the past decades on the young alluvial soils did not show a significant yield response. Exchangeable soil K was found medium-low to medium and a greenhouse exhaustion study showed depletion of soil K and severe K deficiency in the second crop. Unbalanced fertilisation with high NP and low K application in intensive rice cropping systems may generate soil K depletion. The concern that K deficiency could be a severe problem for rice cultivation in the Mekong Delta in the near future and the need for a better understanding why results of field trials were conflicting formed the incentive for the study described in this thesis.

The K budgets of soil-rice systems are a function of cropping intensity, irrigation and flooding regime, fertiliser used and straw management, but currently there is little quantitative insight. Therefore, K budgets of specific rice cropping systems should be assessed to be able to evaluate the various alternatives for managing K. Such knowledge forms the basis of designs of decision support systems for K management aimed at economically and environmentally sustaining high yields and maintaining soil K at target level.

There is a great need of suitable methods for characterising different K pools to be used in models on K dynamics. Many studies have provided information about the reliability of simple extraction methods for K, such as 0.01 M $CaCl_2$, 1 M NH_4OAc pH 7, 1 M HNO_3, NaTPB, as indicators of plant available K on the (very) short, but not on the long run. Reports on kinetics of K adsorption and fixation-release processes carried out in the laboratory do present rate coefficients of K transfers among pools, but these have rarely been compared to rate coefficients as found under cropping conditions in the field, nor they have been used for a predictive understanding of the short- and long-term ability of soils to supply K to crops.

The main objectives of the present research were to get quantitative insight in K budgets of intensive rice cropping systems and to acquire the knowledge on K dynamics needed for K management for sustainable intensive rice cultivation. Specific objectives of the research were:

(i) to quantify K budgets of double and triple rice crops with detailed measurements of K inputs and outputs,

(ii) to assess the chemical extraction methods that best describe the size of the various functional pools of soil K,

(iii) to evaluate equations for the description of kinetics of K adsorption-desorption and fixation-release,

(iv) to study the effects of water management, K application and soil type on soil K dynamics and crop K uptake in greenhouse experiment,

(v) to develop a model to predict soil K changes over time under cropping conditions, to be used to formulate proper K management for rice soils in the Mekong Delta.

Chapter 1 deals with the geography and the rice cropping systems in The Mekong Delta, and introduces the related K problems.

In Chapter 2, K budgets with complete measurement of all inputs and outputs of K are assessed for some specific areas, representing double and triple rice cropping systems on flooded alluvial soils. In a double cropping system with low sediment input and complete removal of rice straw and no addition of fertiliser K, K balances were negative (70-45 per ha per yr) for K (soluble), K(NH_4OAc), K(NaTPB), but positive for total K (250-365 kg per ha per yr). In another double cropping area where rice straw was partially removed and about 70 kg fertiliser K per ha per yr was added, balances were about neutral for K(NH_4OAc), and positive (20 kg and 1050 kg K per ha per yr, respectively) for K(NaTPB) and total K. In a triple crop system, where rice straw was partially removed and K fertilizer was applied at 40 kg ha^{-1} yr^{-1}, K balances were negative for K(soluble), K(NH_4OAc), K(NaTPB) (86, 80 and 48 kg K per ha per yr, respectively),and positive for K(total) (1125 kg per ha per yr).

Complete removal of rice straw was the largest K output.

Chemical extraction methods to characterise various functional K pools in the soil are studied in relation to a greenhouse exhaustion experiment (Chapter 3). The increasing order of the amount of extractable K was 0.01 M $CaCl_2$ < 1M NH_4OAc pH 7 < 1 M HNO_3 < 0.2 M NaTPB. All methods were well correlated with plant uptake of K. It was decided to use K(NH_4OAc) for the labile pool, and the difference between K(NaTPB) and K(NH_4OAc) for the intermediate pool in the proposed three-pools model.

Chapter 4 describes experiments on K adsorption, desorption, fastening and removal in the laboratory. For simulation of adsorption and fastening, soils were percolated with a solution of 50 mg K l^{-1}. Soils were leached with 0.01 M $CaCl_2$ for desorption, and with 0.067 M NaTPB for simulation of K removal. First order equations described well the adsorption, fastening and desorption processes. It was found that the rate coefficient of removal with NaTPB decreased over time; this decrease could be accounted by the so-called Yang and Janssen equation. K adsorption was positively related to organic C and clay contents, and K fastening was positively related to silt and NaTPB contents. Initial K release rate was related to K(NH_4OAc) and K(NaTPB).

Chapter 5 deals with another greenhouse experiment. Three rice crops were grown successively; between two crops soils were left uncropped for 25 days. Treatments were wet and dry water management in the periods between two crops, application or no application of K fertiliser, and soil type (4 soils). Results showed that water management between two successive crops had no significant influence on K(NH_4OAc) and K(NaTPB) of the soils, and on grain yield and K uptake. All soils were low in K(NH_4OAc) and K(NaTPB). Slight K deficiency occurred in the first crop as shown by low K mass fractions in the plant. Severe K deficiency occurred in the second and third crops when no fertiliser K was applied. Because K(NaTPB) and hence the intermediate K, did not decrease over time. It was concluded that K(NaTPB) is not suitable for the assessment of the intermediate pool in a three-pools model.

In Chapter 6, the two models, called Parallel and the Series model were tested using the results of the two greenhouse experiments. The Parallel model has found useful for a simple interpreting of experimental data to identify the source of K uptake, but it was unable to predict future soil K changes and K uptake. The Series model could better predict the dynamics of soil K pools and the future of K uptake. The test of a three-pools model failed because the analysis of the intermediate pool was not reliable. A reduced Series model with only two pools (labile and recalcitrant K), however, was also able to satisfactorily calculate plant K uptake and changes in soil K pools, even for soils that received fertiliser K.

Chapter 7 discusses the major findings in the study, and suggests future researches, and outlines a decision support system scheme on soil K management based on application of the Series model.

Major findings in the study refer to (i) the advantage of the complete K budgeting approach over the partial approach in assessing the K balance of a system, and the usefulness of a differentiation between pools according to the availability of K in sediments, (ii) the rate coefficients of the transfers between the pools and an equation to describe the decrease in rate coefficients over time, and (iii) the proposed Series model to predict future K uptake and dynamics of soil K.

In conclusion, the information K budgets, the knowledge on K dynamics and the modelling approach in this study have improved the understanding of K behaviour in rice soils and provide the ingredients for as decision support system on K management in the Mekong Delta.

Samenvatting

De Mekong Delta (MD) is een belangrijk gebied voor de rijstteelt in Vietnam en meer algemeen in zuidoost Azië. De teelt van rijst is de laatste decennia sterk geïntensiveerd en de rijstopbrengsten zijn fors gestegen. De toename van de opbrengst per ha is mogelijk gemaakt door rijstvariëteiten te gebruiken die een hogere opbrengst kunnen leveren, door meer kunstmest toe te dienen, en door het management te verbeteren. Sinds enige jaren is echter bezorgdheid ontstaan over uitputting van de bodem en over kaliumgebrek in rijst, vanwege de toegenomen afvoer van kalium (K) met de geoogste rijst en door de éénzijdige bemesting (vooral stikstof en een beetje fosfaat).

De rapporten over de K-toestand en de K-balans van de grond, en over de reactie op K-bemesting in de jonge alluviale rijstgronden in the Mekong Delta zijn tegenstrijdig, en de K-bemestingsadviezen zijn niet consequent. Veel bemestingsproeven die de afgelopen decennia zijn uitgevoerd op de jonge alluviale rijstgronden lieten geen significant effect op de opbrengst zien. De waardering voor uitwisselbaar K in de grond viel in de categorie matig tot gemiddeld. Een potproef in de kas liet uitputting van bodem-K zien en ernstig K-gebrek in het tweede gewas. Ongebalanceerde bemesting met hoge giften van N en P en lage van K kan leiden tot uitputting van bodem-K in de intensieve rijstteelt. De bezorgdheid dat K-gebrek een ernstig probleem kan worden voor de rijstteelt in the Mekong Delta in de nabije toekomst en de behoefte aan een beter inzicht in de oorzaken van de tegenstrijdigheden in de resultaten van veldproeven vormden de aanleiding voor de studie die in dit proefschrift wordt beschreven.

De K-budgetten van bodem-rijst systemen zijn een functie van teeltintensiteit, irrigatie en overstromingsregiem, bemesting en de wijze waarop het stro gebruikt wordt, maar er bestaat thans nog weinig kwantitatief inzicht. Om in staat te zijn verschillende alternativen voor K-management op hun waarde te schatten, moeten K-budgetten van specifieke rijstteeltsystemen worden vastgesteld. Dergelijke kennis vormt de basis voor de opzet van beslissingsondersteunende systemen gericht op K-management dat streeft naar economisch en milieukundig duurzaam hoge opbrengsten waarbij K in de grond op het gewenste niveau gehandhaafd blijft.

Er bestaat grote behoefte aan geschikte methoden om de verschillende pools van K in de grond, die gebruikt worden in modellen over K-dynamiek, te karakteriseren. Veel studies hebben informatie verschaft over de betrouwbaarheid van eenvoudige extractiemethoden als indicator voor de beschikbaarheid van K voor de plant op (zeer) korte termijn, zoals 0.01M $CaCl_2$, 1M NH_4OAc pH 7, 1M HNO_3, NaTPB, maar niet als indicator voor de beschikbaarheid op lange termijn. Rapporten over de kinetiek van de processen van adsorptie, fixatie en beschikbaar komen van K uitgevoerd in het laboratorium geven constanten voor de reacties tussen de K-pools in de grond, maar deze zijn zelden vergeleken met de reactiesnelheden die in het veld, in met rijst beteelde grond, zijn gevonden, en ze zijn ook niet gebruikt om voorspellingen te doen over het korte- en lange-termijn vermogen van de grond om K aan het gewas te leveren.

De hoofddoelstellingen van het huidige onderzoek waren om kwantitatief inzicht te krijgen in de K-budgetten van intensieve rijstteeltsystemen en om de kennis te verwerven over K-dynamiek die nodig is voor het K-management van duurzame, intensieve rijstcultuur. Specifieke doelstellingen van het onderzoek waren:

(i) K-budgetten te kwantificeren van systemen met twee of drie rijstgewassen per jaar op basis van gedetailleerde metingen van K-aanvoer en –afvoer;

(ii) vast te stellen welke chemische extractiemethoden het beste de grootte van de verschillende functionale fracties van bodem-K beschrijven;

(iii) de waarde te bepalen van vergelijkingen voor de beschrijving van de kinetiek van adsorptie en desorptie en van vastlegging en vrijkomen van K;

(iv) de effecten te bestuderen van waterregiem, K-toediening en bodemtype op de dynamiek van bodem-K en de opname van K door het gewas in kasproeven;

(v) een model te ontwikkelen dat de veranderingen kan voorspellen die de omvang van de K-pools in de loop der tijd ondergaat in met gewas beteelde grond en dat van nut kan zijn voor de formulering van het juiste K-management van rijstgronden in de Mekong Delta.

Hoofdstuk 1 behandelt de geografie en de rijstteeltsystemen in de Mekong Delta, en introduceert de achtergrond van K-gebrek in de rijstteelt.

In Hoofdstuk 2 worden K-budgetten gepresenteerd, waarbij alle aan- en afvoeren van K zijn gemeten. De K-budgetten zijn opgesteld voor teeltsystemen met twee of drie rijstgewassen per jaar op alluviale gronden die overstroomd worden. Deze teeltsystemen zijn representatief voor de Mekong Delta. . In systemen met twee rijstgewassen, geringe aanvoer van sediment, volledige afvoer van het stro, en zonder K-bemesting, waren de balansen negatief (70-45 per ha per jaar) voor K in oplossing, K(NH_4OAc) en K(NaTPB), maar positief voor Totaal K (250-365 kg per ha per jaar). In een ander systeem met twee rijstgewassen, gedeeltelijke afvoer van het stro en ongeveer 70 kg K-bemesting per ha per jaar, waren de balansen neutraal voor K(NH_4OAc) en positief (20 kg en 1050 kg K per ha per jaar, respectievelijk) voor K(NaTPB) en Totaal K. In een systeem met drie rijstgewassen, gedeeltelijke afvoer van het stro en 40 kg K-bemesting per ha per jaar, waren de balansen negatief voor respectievelijk K in oplossing, K(NH_4OAc) en K(NaTPB) (86, 80 en 48), en positief (1125 kg K per ha per jaar) voor Totaal K. Volledige verwijdering van het stro was de grootste afvoerpost.

Chemische extractiemethoden om de verschillende functionele K-pools in de grond te karakteriseren werden bestudeerd in samenhang met een uitputtingsproef in de kas (Hoofdstuk 3). De volgorde van toenemende hoeveelheden geëxtraheerd K was 0.01 M $CaCl_2$ < 1M NH_4OAc pH 7 < 1 M HNO_3 < 0.2 M NaTPB. Alle methoden waren goed gecorreleerd met de opname van K door de plant. Besloten werd K(NH_4OAc) te gebruiken voor de labiele pool, en het verschil tussen K(NaTPB) en K(NH_4OAc) voor de intermediaire pool in het voorgesteld drie-pools model.

Hoofdstuk 4 beschrijft laboratorium-experimenten over adsorptie, desorptie, vastlegging en vrijmaking van K. Voor de simulering van adsorptie en vastlegging werden de gronden gepercoleerd met een oplossing van 50 mg K l^{-1}. De gronden werden uitgespoeld met 0.01 M $CaCl_2$ voor desorptie, en met 0.067 M NaTPB om het vrijmaken van K te simuleren. Eerste-orde vergelijkingen konden de processen van adsorptie, vastlegging en desorptie goed beschrijven. Het bleek dat de coëfficiënt voor de reactiesnelheid van het vrijmaken van K met NaTPB in de loop der tijd afnam; deze afname kon worden weergegeven met de zogenaamde Yang en Janssen vergelijking. Er werd een positief verband gevonden tussen de adsorptie van K en de gehalten aan organisch C en klei, en tussen de vastlegging van K en de gehalten aan slib en K(NaTPB). De initiële reactiesnelheid van het vrijmaken van K met NaTPB was gerelateerd aan K(NH_4OAc) en K(NaTPB).

Hoofdstuk 5 gaat over een tweede kasproef. Drie rijstgewassen werden na elkaar geteeld; tussen twee gewassen in bleef de grond gedurende 25 dagen onbegroeid. Behandelingen waren de grond nat houden of laten uitdrogen in de perioden tussen twee gewassen, wel of geen K-bemesting, en bodemtype (4 grondsoorten). De resultaten lieten zien dat het nat of droog houden van de grond tussen twee opeenvolgende gewassen geen significante invloed had op K(NH_4OAc) en K(NaTPB) van de gronden, op de korrelopbrengst en op de K-opname. Alle gronden waren laag in K(NH_4OAc) en K(NaTPB). In het eerste gewas trad een gering K-tekort op dat tot uiting kwam in lage K massa-verhoudingen in de plant. Ernstig K-tekort werd aangetroffen in het tweede en derde gewas wanneer niet met K werd bemest. Omdat K(NaTPB) en dus ook intermediair K niet afnam met verloop van tijd, werd geconcludeerd dat K(NaTPB) niet geschikt is voor de bepaling van de intermediaire pool in een drie-pools model.

In Hoofdstuk 6 werden twee modellen, genaamd het Parallel model en het Serie model, getoetst aan de hand van de resultaten van de twee kasproeven. Het Parallel model was nuttig voor een eenvoudige interpretatie van de experimentele gegevens om de bron voor de K-opname te achterhalen, maar het was niet in staat om toekomstige veranderingen in bodem-K en de opname van K te voorspellen. Het Serie model kon de dynamiek van K-pools in de bodem en de toekomstige K-opname beter voorspellen. De toetsing van een drie-pools model mislukte omdat de analyse van de intermediaire pool niet betrouwbaar was. Een gereduceerd Serie model met slechts twee pools (labiel en recalcitrant K), was evenwel ook redelijk in staat de K-opname door de plant en de veranderingen in de K-pools in de grond te voorspellen, zelfs in gronden die K-bemesting hadden ontvangen.

Hoofdstuk 7 bespreekt de belangrijkste resultaten van de studie, doet suggesties voor toekomsting onderzoek, en geeft de opzet voor een beslissingsondersteunend systeem voor K- management dat gebaseerd is op toepassing van het Serie model.

De belangrijkste resultaten van de studie hebben betrekking op (i) het voordeel van een volledig K-budget boven een partieel budget voor de vaststelling van de K-balans van een systeem, en het nut van een differentiatie van de pools in sedimenten aan de hand van de K-beschikbaarheid; (ii) de coëfficiënten van de reactiesnelheden tussen de pools en een vergelijking om de afname van de reactiesnelheid in de loop der tijd te beschrijven; (iii) het voorgestelde Serie model om de toekomstige K-opname en de dynamiek van K in de grond te voorspellen.

Concluderend kan gezegd worden dat de informatie over K-budgetten, de kennis over de K-dynamiek en de modelmatige aanpak in deze studie het inzicht in het gedrag van K in rijstgronden hebben verbeterd en ingrediënten hebben verschaft voor een beslissingsondersteunend systeem voor K-management in de Mekong Delta.

TÓM TẮT

Đồng Bằng Sông Cửu Long (ĐBSCL) là vùng sản xuất lúa chính ở Việt Nam và ở Đông Nam Á. Các báo cáo về hàm lượng Kali trong đất, cân bằng Kali và sự đáp ứng của lúa đối với phân Kali có nhiều điểm không thống nhất, do đó các khuyến cáo về việc bón phân Kali không nhất quán. Các thí nghiệm phân bón trong vài chục năm qua đã cho thấy không có sự đáp ứng đối với phân Kali. Hàm lượng Kali trao đổi trên đất phù sa được đánh giá ở mức khá thấp đến trung bình. Thí nghiệm trồng kiệt trong nhà lưới cho thấy sự cạn kiệt chất Kali trong đất và sự thiếu Kali trầm trọng ở vụ thứ hai. Việc bón phân không cân đối với liều lượng phân NP cao, nhưng bón rất ít phân Kali trên những vùng lúa thâm canh có thể làm cạn kiệt nhanh chất Kali trong đất. Mối lo ngại về nguy cơ thiếu Kali trong thâm canh lúa ở ĐBSCL trong tương lai gần và sự cần thiết phải tìm hiểu về các kết quả thí nghiệm bón phân Kali trên đồng ruộng đã khởi đầu cho việc nghiên cứu thực hiện trong luận án này.

Nguồn dự trử Kali trong hệ thống đất lúa bị ảnh hưởng bởi sự thâm canh lúa, chế độ nước tưới và chế độ ngập lũ, lượng phân bón sử dụng và sự quản lý rơm rạ. Nhưng điều này ít được nghiên cứu một cách đầy đủ. Do đó nguồn Kali dự trử trong đất của các hệ thống thâm canh lúa cần được xác định để có thể đánh giá các biện pháp khác nhau trong quản lý chất Kali trong đất. Những kiến thức này sẽ là cơ sở cho việc xây dựng một hệ thống hổ trợ quyết định trong việc quản lý chất Kali trong đất nhằm duy trì năng suất lúa cao và hàm lượng Kali đầy đủ một cách kinh tế và có ý nghĩa cao về mặt bảo vệ môi trường.

Việc xăc định phương pháp phân tích thích hợp để đánh giá các thành phần Kali trong đất rất cần thiết cho công tác mô hình hóa sự biến động Kali trong đất. Nhiều nghiên cứu đã cung cấp thông tin về độ tin cậy của các phương pháp phân tích các thành phần Kali trong đất như: 0.01 M $CaCl_2$, 1 M NH_4OAc pH 7, 1 M HNO_3, NaTPB, như là một đánh giá cho hàm lượng Kali hữu dụng trong một htời gian ngắn (hoặc rất ngắn) nhưng không đánh giá được trong một thời gian dài. Những báo cáo về sự hấp phụ và cố định hoặc phóng thích chất Kali được thực hiện trong phòng thí nghiệm đã xác định được các hệ số của sự chuyển đổi giữa các thành phần Kali, nhưng những hệ số này ít được so sánh với các hệ số được tìm thấy trong điều kiện canh tác ngoài đồng, cũng như không được sử dụng cho việc dự đoán khả năng cung cấp chất Kali ngắn hạn và dài hạn cho cây trồng.

Mục tiêu chính của nghiên cứu này là đánh giá lượng Kali dự trữ trong hệ thống thâm canh lúa và tìm hiểu về sự biến động Kali trong đất cần thiết cho sự quản lý chất Kali trong việc canh tác lúa bền vững. Những mục tiêu chuyên biệt của nghiên cứu là:

(i) Định lượng nguồn dự trữ Kali trong hệ thống thâm canh hai vụ và ba vụ lúa với việc đo lường chi tiết các nguồn thu nhập và mất chất Kali trong đất,

(ii) Xác định phương pháp phân tích thích hợp cho việc đánh giá các thành phần Kali trong đất,

(iii) Xác định phương trình thích hợp cho sự hấp phụ-trao đổi và cố định-phóng thích,

(iv) Nghiên cứu ảnh hưởng của sự quản lý nước, việc bón phân Kali và loại đất trên sự biến động chất Kali và sự thu hút Kali trong thí nghiệm nhà lưới,

(v) Xây dựng mô hình dự đoán sự biến động chất Kali theo thời gian trong điều kiện canh tác để có thể đề nghị biện pháp quản lý Kali thích hợp trong canh tác lúa ở ĐBSCL

Chương 1 đề cập đến địa lý ĐBSCL và hệ thống canh tác lúa ở đồng bằng, và giới thiệu những vấn đề liên quan đến chất Kali trong canh tác lúa.

Trong Chương 2, các nguồn thu nhập và mất chất Kali trong đất được đo lường một cách chi tiết cho một vài vùng chuyên biệt, đại diện cho hệ thống canh tác lúa hai và ba vụ ở vùng đất phù sa bị ảnh hưởng chế độ ngập lũ. Ở vùng canh tác hai vụ ít được bồi, rơm rạ bị lấy đi hoàn toàn và không bón phân Kali, cân bằng Kali âm (70-45 kg $ha^{-1}năm^{-1}$) đối với K (hoà tan), K (NH_4OAc), K (NaTPB), nhưng cân bằng Kali dương đối với K tổng số (250-365 $kg.ha^{-1}.năm^{-1}$). Ở một vùng canh tác lúa hai vụ khác, nơi rơm rạ bị lấy đi một phần và phân Kali được bón ở mức 70 $kg.ha^{-1}.năm^{-1}$, thì đạt được sự cân bằng đối với K (NH_4OAc), và đạt cân bằng dương (20 và 1050$kg.ha^{-1}.năm^{-1}$) đối với K (NaTPB) và K tổng số, theo thứ tự. Ở hệ thống canh tác ba vụ lúa, nếu rơm rạ bị lấy đi một phần và phân Kali được bón ở mức 40 kg ha^{-1} $năm^{-1}$, cân bằng Kali âm (86, 80, và 48 kg $ha^{-1}năm^{-1}$) đối với K (hoà tan), K (NH_4OAc), K (NaTPB), theo thứ tự, và cân bằng dương đối với K tổng số (1125$kg.ha^{-1}.năm^{-1}$). Sự lấy đi hoàn toàn rơm rạ là nguồn mất Kali lớn nhất.

Những phương pháp phân tích các thành phần Kali trong đất được nghiên cứu trong thí nghiệm nhà lưới (Chương 3) cho thấy thứ tự gia tăng dần của hàm lượng Kali trích được là 0.01M $CaCl_2$ < 1M NH_4OAc pH7 < 1M HNO_3< 0.2M NaTPB. Tất cả các phương pháp trích đều tương quan chặt với sự thu hút Kali bởi cây trồng. K (NH_4OAc) được đề nghị để đánh giá K di động, và sự khác biệt giữa K (NaTPB) và K(NH_4OAc) được đề nghị để đánh giá thành phần K trung gian ít di động trong mô hình ba thành phần Kali.

Chương 4 thảo luận thí nghiệm về sự hấp thụ, trao đổi, cố định và phóng thích Kali trong phòng thí nghiệm. Để nghiên cứu sự hấp phụ và cố định Kali, đất được rữa với dung dịch 50 mg K l^{-1}. Đất được rữa với 0.01M $CaCl_2$ để nghiên cứu sự trao đổi và với 0.067M NaTPB để nghiên cứu sự phóng thích Kali. Sự hấp phụ, cố định và trao đổi được mô tả thích hợp bằng phương trình vi phân bậc nhất. Kết quả nghiên cứu cho thấy hệ số phóng thích Kali được nghiên với dung dịch NaTPB thì giảm theo thời gian, sự giảm này có thể được diễn tả bằng phương trình được gọi là Yang-Janssen (2000). Sự hấp phụ Kali thì tương quan thuận với carbon hữu cơ và hàm lượng sét, K cố định thì tương quan thuận với hàm lượng sa cấu thịt và NaTPB. Hệ số phóng thích K ban đầu thì tương quan với K (NH_4OAc) và K (NaTPB).

Chương 5 đề cập đến một thí nghiệm nhà lưới khác. Lúa được trồng liên tục ba vụ với thời gian trống giữa hai vụ là 25 ngày. Các nghiệm thức là chế độ nước ngập và khô giữa hai vụ, bón hoặc không bón phân Kali, và loại đất (4 loại đất). Kết quả nghiên cứu cho thấy chế độ quản lý nước giữa hai vụ không có ảnh hưởng đến K (NH_4OAc) và K (NaTPB) trong đất, năng suất và K thu hút bởi cây trồng. Tất cả các loại đất đều có hàm lượng K (NH_4OAc) và K (NaTPB) thấp. Sự thiếu Kali đã xuất hiện ở vụ thứ nhất, ghi nhận được bởi làm lượng Kali thấp trong cây. Sự thiếu Kali trầm trọng xãy ra ở vụ thứ hai và thứ ba ở các nghiệm thức không bón Kali. Vì K (NaTPB) không giảm và do đó K trung gian cũng không giảm theo thời gian. Điều này có thể đưa đến kết luận là K(NaTPB) không thích hợp để đánh giá thành phần K trung gian ít di động trong mô hình ba thành phần Kali.

Ở chương 6, hai mô hình được gọi là "Parallel" và "Series" được thử nghiệm, sử dụng kết quả của hai thí nghiệm nhà lưới. Mô hình "Parallel" được tìm thấy hữu dụng cho việc xác định nguồn Kali thu hút từ các thành phần Kali của các thí nghiệm, nhưng không thể dự đoán sự thay đổi và sự thu hút Kali trong thời gian dài. Mô hình "Series" có thể dự đoán sự biến động các thành phần Kali và sự thu hút Kali bới cây trồng theo thời gian. Việc thử nghiệm mô hình ba thành phần Kali không được thực hiện vì phương pháp phân tích thành phần K trung gian ít di động không tin cậy. Tuy nhiên, việc áp dụng mô hình "Series" hai thành phần có thể tính toán một cách thích hợp sự thu hút Kali và sự biến động các thành phần Kali theo thời gian, ngay cả đối với đất đã đượn bón phân Kali.

Chương 7 thảo luận những kết quả chủ yếu trong nghiên cứu này và đề nghị những nghiên cứu trong tương lai va` đã phát thảo khung hệ thống hổ trợ quyết định về sự quản lý chất Kali dựa vào việc áp dụng mô hình "Series".

Những kết quả chủ yếu của đề tài là: (i) ưu điểm của phương pháp tính toán toàn bộ nguồn dự trử Kali trong đất so với phương pháp tính toán một phần trong việc đánh giá sự cân bằng của một hệ thống và sự hữu dụng của việc phân biệt các thành phần Kali trong việc tính toán sự thêm vào chất Kali bởi phù sa, (ii) hệ số của sự chuyển đổi giữa các thành phần Kali và phương trình để mô tả sự giảm của hệ số phóng thích chất Kali theo thời gian, (iii) mô hình "Series" được đề nghị để dự đoán sự thu hút Kali và sự biến động của Kali trong đất theo thời gian.

Để kết luận, thông tin về nguồn K dự trữ, kiến thức về động thái chất Kali và phương pháp mô hình hoá trong nghiên cứu này đã làm tăng sự hiểu biết về đặc tính của K trong đất lúa và cung cấp các thành phần cần thiết trong hệ thống hổ trợ quyết định về sự quản lý chất Kali trong canh tác lúa ở ĐBSCL.

Curriculum vitae

The author was born in Can Tho Province, Vietnam on 24 July 1956. She is the third child of Mrs. Ngo Thi Ba and Mr. Nguyen Ba Thao.

She completed her elementary and secondary education from Tan An Elementary school and Doan Thi Diem High school in Can Tho Province. She obtained the B.Sc.'s degree in Agronomy from Can Tho University, Vietnam, in 1979.

After her graduation, she worked at the Department of Rice Science, Faculty of Agriculture, Can Tho University, as a researcher. In November 1979, she was granted a training scholarship by the Vietnam – Holland collaborative project to study methods of soil analysis on Acid Sulfate Soils at the Wageningen Agricultural University, The Netherlands. After the course, she worked at the Soil Science Department of Can Tho University as a lecturer and researcher.

In 1989, she was again granted a training scholarship on fertilizer recommendation at the Wageningen Agricultural University and Institute of Soil Fertility and Fertilizer in Groningen, The Netherlands.

From 1994 to 1997, she held a scholarship from the Swedish Agricultural Research and Education Cooperation (SAREC), enabling her to pursue a Master of Science degree in Soil Science at the University of the Philippines-Los Banos, the Philippines.

In 1999, she obtained a scholarship from the International Rice Research Institute to follow the sandwich Ph.D. program at the Sub-Department of Soil Quality, Department of Environmental Sciences, Wageningen University, The Netherlands.

She is married to Nguyen Phu Hai and they have two sons, Nguyen Phu Tam and Nguyen Duc Tam.