SOIL-IMPROVING CROPPING SYSTEMS FOR SUSTAINABLE RICE PRODUCTION IN THE VIETNAMESE MEKONG DELTA

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Dedicated to the farmers in the Mekong Delta, Vietnam

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List of abbreviations

ANOVA	Analysis of Variance
B	Boron
B/C	Benefit-cost ratio (Gross return/Total cost)
BD	Bulk density
Ca	Calcium
CEC	Cation Exchange Capacity
$C_{hydrolysable}$	Carbon HCl hydrolysable
Cu	Copper
DASP	Days After Soil Preparation
DMRT	Duncan's Multiple Range Test
EC	Electric Conductivity
EDTA	Ethylene Diamine Tetra Acetic acid
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
Fe	Ferrous
IS	Instability Index
K	Potassium
K_{fs}	Field-saturated hydraulic conductivity
Ksat	Saturated hydraulic conductivity
MacP	Macro-porosity
MatP	Matrix porosity
Mg	Magnesium
Mn	Manganese
MWD_{dry}	Mean weight diameter after dry seiving
MWD_{wet}	Mean weight diameter after wet seiving
N	Nitrogen
Ni	Nickel
P	Phosphorus
PAWC	Plant Available Water Capacity

PD	Particle density
PN	Panicle number
PR	Penetration resistance
PWP	Permanent wilting point
r	Coefficient of correlation
R^2	Coefficient of determination
RD	Rooting depth
RH	Rice height
R-Mb-M	Rice–mung bean–maize
R-Mb-R	Rice–mung bean–rice
RMD	Root mass density
R-M-R	Rice–maize–rice
RRR	Rice–rice–rice (of farmers' fields)
R-R-R	Rice–rice–rice (of experimental field)
RUR	Rice-Upland crop-Rice
RUU	Rice-Upland crop- Upland crop
S	Sulphur
SA	Summer -Autumn season
SB	Straw biomass
SI	Stability index
Si	Silicon
S_{index}	S index of Dexter (2004)
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SP	Soil porosity
SPSS	Statistical Package for Social Science
SS	Spring-Summer season
STDEV	Standard Deviation
TA	Total acidity
Tmax	Maximum temperature
Tmean	Mean temperature
Tmin	Minimum temperature

UNEP	United Nations Environment Programme
UUU	Upland crop- Upland crop- Upland crop
WS	Winter Spring season
Y	Yield
Zn	Zinc
θ_{FC}	Soil water content at field capacity
θ_{PWP}	Soil water content at permanent wilting point
θ_r	Residual soil water content
θ_s	Soil water content at saturation
ψ	Matric head

Summary

In the Vietnamese Mekong Delta, rice production is important for the socio-economic development. Continuous paddy rice cultivation with three rice crops per year is the major cropping system. However, farmers are currently confronted with problems of declining land productivity. A declining trend in rice yield has been exhibited over recent years, despite the efforts of farmers to increase rice yield by applying chemical fertilizer even above recommended rates. We hypothesized that the yield decline was associated with a decline in soil quality resulting from the specific tillage operations and the continuous anaerobic conditions that are characteristic for continuous paddy rice cultivation in monocultures. This study was carried out in order to test alternative cropping systems that might contribute to improve soil quality and thus mitigate the negative effects of the present rice monoculture practices on soil quality, conserve the natural land resources and support sustainable agricultural production in this area. The overall objective of this dissertation was to evaluate the effects of different cropping systems with different rotations of rice with upland crops on physical and chemical properties of an alluvial paddy clay soil in a long-term field experiment. In addition, the effect of rotating rice with upland crops on rice yield components, and economic profitability was investigated to better understand and evaluate the sustainability of the new cropping systems in the Mekong Delta, Vietnam.

The experimental field had been intensively used for rice monoculture for more than 30 years, prior to our study. A long-term rice-upland crop rotational field experiment was then conducted using a randomized complete block design with four cropping systems and four replications. The cropping systems were: (i) traditional intensive rice monoculture with three rice crops per year (designated as R-R-R), (ii) rotation with two rice crops and maize (designated as R-M-R), (iii) rotation with two rice crops and mung bean (designated as R-Mb-R) and (iv) rotation with one rice and two upland crops - mung bean and maize (designated as R-Mb-M).

Additionally, a farm household survey was conducted among farmers, in which information on household characteristics, farm cropping activities, farm production practices and performance and household income was collected. Four types of

farming practices were observed, one based on traditional rice monoculture with three rice crops per year (RRR), one based on a crop rotation with two rice crops and one upland crop (RUR), one based on a crop rotation with one rice and two upland crops (RUU), and a fourth based on upland crop monocultures (UUU).

Results show significant improvement in soil physical and chemical properties for cropping systems with two rice crops and one upland crop (R-M-R and R-Mb-R) and those with one rice crop and two upland crops (R-Mb-M) compared to intensive rice monoculture (R-R-R). This was translated in decreased bulk density and soil penetration resistance, increased soil organic carbon content, a presumed hydrolysable labile carbon fraction and total porosity, and higher aggregate stability index, plant available water capacity and Dexter's S index, especially at depths of 10-20 and 20-30 cm. Improvements in soil properties were not only observed at the end of the spring-summer season (dry season) during which upland crops were cultivated in the rotations with upland crops, but also in the winter-spring season (late wet season) when rice was cultivated on the plots of all treatments. As a consequence, rice rooting depth and root mass density strongly increased in all rice-upland rotation systems. This resulted in a higher plant height, total number of tillers and panicles, filled grain percentage and a rice yield that was 32–36% higher compared to the control. Farmer's profitability even increased 2.5 to 2.9 times. Rotations of rice with upland crops yielded higher gross return due to higher rice yield and good prices for mung bean and maize, though they came with higher total costs, primarily due to land preparation and harvest.

Our findings show that rice growth and yield was dependent on rice root growth, which was affected by soil compaction as reflected by bulk density, porosity, penetration resistance, macro-porosity, aggregate stability index, soil organic matter decomposition degree (i.e., $C_{\text{hydrolysable}}$) and soil organic carbon content of the compacted layer (20-30 cm depth) but not by soil organic carbon stocks (0-30 cm). Alleviating soil compaction as in the rice-upland crop rotation made an important contribution to increasing rice root growth. Rooting zone stocks of almost all macro, meso (N, P, K, Ca, Mg, S) and micro nutrients (Mn, Fe, Si, Cu, B, Ni, Zn) were higher in rice-upland crop rotation systems compared to rice monoculture system, which also explained the higher yields. We found relations between rice yield and nutrition available stocks through enhanced rooting depth. With root growth being determined by physical soil quality, the latter thus indirectly affect yield as well.

The positive effects of rice-upland crop rotation systems on soil quality are linked with deep tillage when preparing the land for upland crop cultivation and anaerobic-aerobic cycles. This results in alleviation of soil compaction and promotes soil organic carbon decomposition, hence increasing rooting depth and root mass density and therefore enhancing rice yield by increasing the amount of available nutrients. Although soil properties and rice yield were affected by the cropping systems, we did not find significant differences in soil quality, and in rice growth and yield between the two types of upland crops, i.e. the non-leguminous maize and the leguminous mung bean, nor between rotation systems with one or two upland crops.

Results show that temporal variability of soil bulk density, macro-porosity and matrix porosity within both seasons and between seasons was limited for cropping systems with upland crop rotations, whereas within season variation was significant for the rice monoculture system, especially at 0-10 cm depth. The stronger increase in bulk density and decline in macro-porosity and field saturated hydraulic conductivity from the early stage of the cropping season (15 days after soil preparation - DASP) towards the middle and the end of the season (45 and 90 DASP) in rice monoculture systems as compared to rice-upland crop rotations could be associated with aggregates being less stable as reflected by their lower soil aggregate stability index. The field saturated hydraulic conductivity of the topsoil showed great temporal variability, both seasonal and inter-seasonal, in correspondence with macro-porosity.

The findings from our long-term field experiment were supported by the data collected during the interviews with the farmers. On farmers' fields, rice rotated with one or two crops (RUR or RUU) also gave higher rice yields than a rice monoculture system (RRR). The rice yield in the last five years increased when rotations with upland crops were implemented, which strongly contrasted with the rice yield under rice monoculture system. The benefit-cost ratio was also higher in the rice-upland crop systems (RUR and RUU) or upland crop monoculture (UUU) than in the prevailing rice monoculture. Interestingly, farmers applied less fertilizer for rice production in RUR and RUU compared to RRR. The survey revealed that many farmers had a tendency to apply too much nitrogen as a way to compensate for the reduced rice growth due to land degradation in RRR. The major challenge in implementation of upland crop production as revealed by farmers was lack of capital investment, low level of technological skills and an unfavorable marketing system.

Most of the tested soil properties in the farmers' fields showed significant differences among cropping systems. Rotations with upland crops (RUR and RUU) and upland crop monocultures (UUU) alleviated soil compaction, resulting in reduced penetration resistance and bulk density and increased total and macro-porosity at 20-30 cm depth, confirming the outcomes of the long-term field experiment. Also aggregate stability index and plant available water capacity were higher for RUR, RUU and UUU at the 20-30 cm depth as compared to RRR. The SOC stock was significantly affected by the cropping system with the lowest value in UUU, whereas, $C_{hydrolysable}$ was greater in rice-upland crop systems (RUR and RUU) or upland crop monocultures (UUU) than rice monocultures (RRR).

Taken all together, the results from both the long-term field experiments and the farmer's fields confirm that rice-upland crop systems can help in alleviating soil degradation resulting from continuous mono cultivation systems. These alternative systems resulted in changes in soil physical and chemical properties. Those changes were concomitant with changes in rice growth and rice yield. However, without carefully planning and connection to the market there is a potential risk for market over supply of upland crop products. The results of this dissertation showed that rice and upland crop rotations coupled with appropriate tillage are soil-improving cropping systems that need to receive more attention in the Mekong Delta in order to cope with soil degradation that was observed in continuous paddy monoculture areas. It is believed that soil-improving cropping systems with upland crop-rice rotations not only help farmers to increase their income, but also contribute to rural development and sustainable agriculture.

Chapter 1

General introduction and objectives

1.1. Soil-improving cropping systems and crop production

1.1.1 The role of soil-improving cropping systems in alleviation soil degradation

Soil degradation is the decline in soil quality or reduction in soil productivity and environmental capacity. The loss of actual or potential soil productivity can result from the impact of natural or anthropogenic factors (Lal, 1997; Lal and Stewart, 1990; Lal et al., 2007), including crop intensification and unsuitable agricultural practices (Ramos et al., 2011). Soil degradation can be physical, chemical or biological. Among these classes, physical soil degradation is likely the most difficult to reverse. Bradford and Peterson (2000) indicated that the major benefits of soil-improving cropping systems such as conservation agriculture can be assessed only after they have been in place for a decade or more.

1.1.2 Soil compaction: deterioration of soil quality

Soil compaction has been identified as one of the leading problems inducing soil degradation (Canillas and Salokhe, 2002) with dramatic effects on soil functions (Schjønning et al., 2013). It is defined by the Soil Science Society of America (1996) as "the process, by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density". Van den Akker and Soane (2005) defined compaction as "a process of densification and distortion in which total and air-filled porosity and permeability are reduced, strength is increased, soil structure partly destroyed, and many changes are induced in the soil fabric and in various characteristics". Nowadays, soil compaction in agricultural soils can be found in a wide range of soils and climates and thus is an increasingly challenging worldwide problem for crop production and environment (Van Ouwerkerk and Soane, 1994; Soane and Van Ouwerkerk, 1995; Mosaddeghi et al., 2000; McGarry, 2001; Hamza and Anderson, 2005; Batey, 2009). Indeed, compaction can have a combined impact of decreased water storage, through the loss of soil porosity, and decreased root growth, through an increase in soil bulk density and soil strength (Arvidsson, 2001;

Ishaq et al., 2001a; Whitmore et al., 2010). Another important process of soil compaction is decline in soil structure. Thomaz and Luiz (2012) stated that weakness of soil structures causes an increase in particle detachment, crust formation and runoff. Moreover, soil compaction also affects some important factors such as mineralization of soil organic carbon and nitrogen (De Neve and Hofman, 2000), the concentration of carbon dioxide in the soil (Conlin and van den Driessche, 2000) as well as diffusion rate of heat (Usowicz et al., 1995) or air and water transport (Berisso et al., 2013).

Several studies stated that most of the soil compaction in agricultural soils is caused by the heavy load from farm machinery traffic, which is an integral part of soil management systems. This results in deeper stress penetration and subsoil compaction (Van den Akker and Stuiver, 1989). It impacts soil aggregates by altering the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units (Defossez and Richard, 2002). This leads to soil degradation and makes considerable damage to the structure of the tilled soil and subsoil (Defossez and Richard, 2002; Horn, 2002; Horn and Fleige, 2003; Peth et al., 2006; Zink et al., 2011; Suzuki et al., 2013). Such inappropriate soil management practices create a hardpan and are some of the reasons behind low crop yield. The depth of the compaction layer varies widely from 10-60 cm for upland field (Flowers and Lal, 1998) and from 10-50 cm for paddy field (Khoa, 2002) depending on soil management.

In addition, soil tillage in intensive farming areas has to be performed frequently, increasing the probability of land preparation when the soil is wet which also promotes soil compaction (Poesse, 1992) and as a result affects plant growth (Dexter, 1999). According to Soane and Van Ouwerkerk (1994), soil water content is the most important factor influencing soil compaction processes. Tillage at excessive soil water content exacerbates the compaction process. Indeed, increasing soil moisture content causes a reduction in load support capacity of the soil (Kondo and Dias Junior, 1999) thus decreasing the permissible ground pressure (Medvedev and Cybulko, 1995). Soil type also influences soil compaction. Ellies et al. (2000) reported that in soil with coarse texture, the dominant penetration of stress was in the vertical direction, while in soil with a finer texture stress propagation was multidirectional.

Soil compaction *in situ* can originate from natural soil processes, farming systems, tillage practices, human activities and time. Soils with high clay content typical of wetlands and river bottoms can become readily compacted by natural processes. Since individual clay particles are so small, they are more susceptible of being pressed together tightly. Subsurface hardpans also develop from precipitation of iron, manganese and silicon (Sharma and De Datta, 1985a). Generally, soil compaction is considered as a function of soil bulk density, soil porosity, soil strength and soil moisture content (Suzuki et al., 2013). Therefore, for the assessment of changes in soil fabric due to compaction, soil bulk density, soil strength, water and structural measurements are widely used to characterize the state of soil compactness and assess the soil quality after compaction (Canarache, 1991; Panayiotopoulos et al., 1994; Guerif, 1994; Horn and Rostek, 2000; McQueen and Shepherd, 2002; Hamza and Anderson, 2003; Sudduth et al., 2008).

1.1.3 Plant response to soil compaction

Soil compaction displays both positive and negative effects on plant growth according to the degree of compaction. One striking effect of soil compaction on plant growth is that it can promote a good seed and soil contact, resulting in faster germination; also plants can more easily take up nutrients and water in soil. Furthermore, soil compaction can decrease water loss by evaporation. In fine textured soils, a bulk density of 0.9-1.2 Mg m^{-3} is generally favorable for root growth and crop production (Reynolds et al., 2003; Reynolds et al., 2007). Commonly, for fine-textured soils, bulk density values of 1.25 to 1.30 Mg m^{-3} are considered as the upper limits for agricultural purposes (Reynolds et al., 2007). In acid sulfate soils, a compacted soil layer might prevent capillary rise from the underlying sulfuric subsoil horizons of toxic acidity levels to the soil surface (Ni and Hanhart, 1992).

Some disadvantages of soil compaction, however, are also intrinsic to crop cultivation. Surely, soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which lead to additional fertilizer requirement and increasing production cost. Moreover, compacted soil may restrict root growth. According to Lipiec et al. (1991) crop yield decreases in over-compacted soils are mostly associated with the extent and function of the root system. A common response of the root system to increasing compaction levels is decreased root size, retarded root penetration and smaller rooting depth (Glin’ski and Lipiec, 1990). Decreased downward extension of roots can result in less water and nutrient uptakes due to reduced volume of soil exploitable by the crop (Glin’ski and Lipiec, 1990; Miransari et al., 2009). Andersen et al. (2013) estimated that subsoil compaction reduced the soil water available in the root-zone by up to approximately 9 cm of water. A second detrimental sequence then occurs of reduced rooting depth and plant growth leading to lower inputs of fresh organic matter to the soil, thereby reducing nutrient recycling, mineralization and microbial activity (Hamza and Anderson, 2005).

A high degree of compaction can have an adverse effect on crop yields, depending on the kind of crop. Arvidsson and Håkansson (2014) found that for barley moderate compaction even led crop yield to increase significantly compared with zero trafficking and previously loosened soil. Annual dicotyledonous crop roots are the most sensitive to soil compaction. They observed the greatest yield losses associated with soil compaction for horse bean, peas, potato and sugar beet whereas compaction in reduced tillage did not result in severe reduction of yield for cereals (wheat, barley, oats). Ni (1995) reported that for clay soil, a BD value higher than 1.35 Mg m^{-3} entails susceptibility to compaction of the paddy subsoil layer which leads to limited root elongation and reduced rice yield.

Generally, plant roots cannot penetrate in very compacted soils. The inability of plant roots to penetrate compacted soil layers is well documented in the literature (Kirkegaard et al., 1992; Venezia et al., 1995; Laker, 2001). Root penetration is restricted as soil strength increases (Mason et al., 1988). Generally, root penetration is severely restricted at >2 MPa (Silva et al., 2000) and ceases entirely with a soil strength higher than 2.5 MPa (Taylor, 1971). The crop yield can only approach the yield potential on uncompacted soil, which can require at least two to seven years of recovery efforts after soil compaction. Slower yield recovery commonly occurs on soils which are higher in clay content (Swan et al, 1987).

1.1.4 Solutions for soil compaction problems

There are many ways to control soil compaction, such as addition of organic matter, controlled traffic, mechanical loosening like deep ripping, and selecting rotations which include crops with strong tap root able to penetrate and break down compacted soil (Hamza and Anderson, 2005; Schjønning et al., 2015). Indeed, roots of different crop species, as well as of cultivars within species, differ considerably in their ability to penetrate through hard soil layers (Singh and Sainju, 1998). Plant species that have the capability to penetrate soils with high strength usually possess a deep tap root system. Incorporating such species in the rotation is desirable to minimize the risks of subsoil compaction (Ishaq et al., 2001b). Their response is related to the ability of the root system to overcome the soil strength limitation of compacted soil (Kirkegaard et al., 1992). In an experimentally compacted soil, Chen and Weil (2010) found that two tap-rooted cover crop species in the Brassicas family had more root biomass at the 15-50 cm depth than did a fibrous-rooted species (cereal rye). Schjønning et al. (2015) reported that tap-rooted species may have the potential to alleviate compacted soil by creating or perhaps by enlarging existing vertical bio-pores.

Additionally, Cochrane and Aylmore (1994) reported that legumes are more effective for stabilizing soil structure than are non-legumes. Indeed, some legume species (especially lupines) are able to grow in compacted soil and loosen compaction through their diurnal changes in root diameter. This was confirmed by Alam (2010), who noticed that crop production could be increased by selecting suitable crops in the cropping pattern, including leguminous crops. Ahmad et al. (2010) reported that inclusion of upland crops, especially legumes, in crop rotations would help to restore the soil natural fertility and crop productivity. Rotations with legume crops can increase soil nitrogen availability for the cereal crop through symbiotic N_2-fixation by the legume (Pierce and Rice, 1988) and improved nitrogen use efficiency (Lassaletta et al., 2014; Anglade et al., 2015). Rotations with these crops minimize the risk on subsoil compaction and improve soil structure. Moreover, crop rotation is known to have a beneficial influence on many soil chemical properties including organic carbon, nitrogen supply, pH and availability of phosphorus, potassium, calcium, magnesium (Power, 1990; Godsey et al., 2007).

Soil organic matter plays a key role in soil aggregation and structuring processes, and has an influence on soil chemical as well as hydro-physical functions (Horn and Smucker, 2005). However, most soils are not in balance as regards soil organic matter contents, as they have been affected by land management practices and land use (Smith et al., 2005). Adding organic matter to the topsoil for improving soil bulk density and porosity has been widely studied by many researchers (Soane, 1990; Ohu et al., 1994; Hamza and Anderson, 2003; Watanabe et al., 2009). Kumar et al. (2009) found that the susceptibility of soils to compaction was reduced when organic carbon levels were elevated. Nevertheless, using organic matter to improve subsoil compaction is less common. The reason behind this is technical and economical, especially in paddy soils. In flooding paddy rice soil, soil organic matter content is already high, and therefore the type of organic matter is more important. On the other hand, readily oxidizable soil organic matter seems to be more relevant than total organic matter in determining mechanical behavior of the soil (Ball et al., 2000).

Deep soil preparation is one of the most important practices for eliminating soil compaction, destroying hard pans and eliminating crusting soils (Laker, 2001; Torella et al., 2001; Hamza and Anderson 2002). It has become a common management technique used to shatter dense subsurface soil horizons which limit percolation of water and penetration of roots (Bateman and Chanasyk, 2001). However, Schafer-Landefeld et al. (2004) observed that if a plow pan is mechanically loosened, it can lead to serious re-compaction. Hallett et al. (2012) reviewed the literature and also emphasized the importance of avoiding re-compaction.

To evaluate soil sensitivity to compaction for decision making, different models have been developed, e.g., by Horn et al. (2005) and Van den Akker (2004), who used a more deterministic approach to assess compaction risk by comparing calculated strengths of a series of soils with stresses exerted by a wheel load. In addition, Peth et al. (2010), Berisso et al. (2012) and Keller et al. (2012) investigated the consequences of deformation for the soil pore system, the gas and liquid transport in disturbed soils, including theoretical approaches (modeling) and empirical findings. Hence, understanding of the changes in soil compaction with changes in water content and bulk density is necessary in planning farm operations at suitable water contents (Arvidsson et al., 2003; Saffih-Hdadi et al., 2009), or in reducing the soil bulk density by applying soil organic matter or appropriate soil tillage (Horn and Smucker, 2005; Hamza and Anderson, 2005; Kumar et al., 2009).

1.2 Rice production and its effect on soil properties

1.2.1 Rice production in the world

Rice (*Oryza sativa* L.) is the most important staple crop for more than half of the world's population (Juliano, 1993, IRRI, 2006). It provides more calories per hectare than any other cereal crop (Singh, 2003) and serves as a primary source of energy for Asian populations (Mandal et al., 2014). Rice is cultivated in at least 114 countries with about 160 million hectare of land globally (FAOSTAT, 2013) that is cultivated in different ways and to different degrees of intensification. Rice production in Asia makes a major contribution to the global rice supply (Cassman and Pingali, 1995; Sahrawat 2005). In 2010, approximately 159 million ha were harvested worldwide, of which 137 million ha (86%) were in Asia, and 48 million ha (30%) were harvested in Southeast Asia only (FAOSTAT, 2012). Equally, rice plays important roles in providing livelihood to the Asian population (Mahapatra and Behera, 2011). Indeed, rice production activities provide employment and generate incomes for several hundred millions people in rural areas who work directly either in rice production or in related support services. In addition, post-harvest operations such as threshing, drying, milling, storing, processing and trading of rice also provide employment for numerous people, particularly in developing countries. Furthermore, rice farming produces straw and husk residues, which are used as renewable energy sources, compost, animal feed, and construction materials; rice production systems also play a role in carbon sequestration (Dat, 1999). Therefore, sustaining rice production is essential for food security and socio-economic development for many countries in the world as well as in Vietnam.

1.2.2 Lowland rice requires a lot of water

Rice is the most productive cereal growing on land at an elevation of sea level to 2,700 m (Sys, 1985) and is the only cereal that can germinate and thrives in water. Surely, rice is the largest consumer of irrigation water (Tuong et al., 2005), with 25-33% of the world's fresh water being used for irrigation exclusively in rice cultivation. It is grown in fields surrounded by earthen levees to retain rain and irrigation water and to ensure soil submergence during the rice cropping period (Pampolino et al., 2008). Rice can be transplanted or directly seeded. Direct seeding under irrigation is the most common form in Europe, Australia and America (Hill et al., 1991) and Vietnam (Xuan and Matsui, 1998).

For flooded paddy cultivation, the field must be leveled to control floodwater and to maintain uniform field water depth. For irrigated intensive rice farming, the slope of the land should be less than 1% so that a uniform water depth can be maintained across the field. A slight slope helps equal water distribution in the field. Therefore, in order to retain impounded surface water on rice fields, soil must have low permeability. The most important soil characteristic for lowland rice cultivation is the presence of an imperviable subsoil layer in the form of a hardpan or massive clay horizon that minimizes the irrigation water infiltration (Saichuk, 2009). In the flooded rice systems, a hardpan is not a problem for water availability because water is readily available to the plant. However, in the upland rice systems, compaction which prevents root growth to deeper soil layers makes rice plants more prone to water stress between irrigations.

1.2.3 Land preparation in rice production and its effect on soil physical properties

Different types of agricultural tools are used in rice farming for initial land preparation (Khurshid et al., 2006) to accomplish diking, leveling, tillage, and puddling. Diking helps to control runoff and leveling ensures uniform water levels in the field which has great impact on rice yield through controlling weeds. Preparatory tillage is practiced to create an optimal physical and edaphological soil condition for better crop growth and yield (Mohanty et al., 2004). For instance, tillage helps to destroy weeds, incorporate crop residues into soil, prepare the seedbed and break hard layers to facilitate root penetration (Prihar, 1990), increase surface retention of water capacity (Lal and Stewart, 1990), avoid soil compaction, establish good crop stand, and minimize soil degradation (Hillel, 1971). Puddling is the most important practice of land preparation for rice. The first step is submerging the soil for at least one day. Afterwards, the soil is puddled under wet conditions with soil water content at field capacity or saturation. Puddling is practiced to provide a soft soil bed for better rice root growth in early stages. Lal et al. (2004) showed that the root system of lowland rice develops better in dense, submerged and puddled soil. Puddling has been reported to increase rice yield even in soils with less than 10 mm day^{-1} permeability. One more striking purpose of puddling in paddy fields is that it helps to control weeds which compete with rice (Smith, 1983) and can cause reduced yield (Baltazar and De Datta, 1992; Moody, 1993).

However, the conventional method of puddling and tillage with heavy machinery also damages the soil and may lead to a decrease in soil physical quality (Mohanty et al., 2004; Bertolino et al., 2010), especially when done under wet soil conditions. The formation of a thick hardpan in the subsoil below the puddled layer is the main long-term effect of puddling on lowland paddy soils. Islam et al. (2005) reported that plow pans form in the same profile under both power tiller and plow treatments, mostly in rice fields. Similarly, Lima et al. (2009) reported that degradation of paddy soils is related to high bulk density and low porosity because of poor soil management. Since the production process involves plowing and puddling under wet conditions and the soil is also kept submerged and anaerobic during the rice crop season, soil aggregates (Tripathi et al., 2005) are dispersed into discrete particles and clog pore spaces (Liu et al., 2005; Verma and Dewangan, 2006). This process could result in increased penetration resistance in the deeper soil up to the depth of tillage (Singh et al., 1998) and thus leads to soil compaction in the subsoil layer (Tripathi et al., 2005).

Besides physical compaction, subsurface hardpans also develop from precipitation of iron, manganese and silicon (Sharma and De Datta, 1985a). The time for hardpan formation is very variable and depends on soil type, climate, hydrology and puddling frequency. Generally, it may take 3 to 200 years for a hardpan to be formed (Moormann and van Breeman, 1978). Compacted layers which occur in lowland rice soils are between 10 and 50 cm depth and have higher dry bulk density and soil strength, and lower total porosity than the over- and underlying soil horizons. Ahmad et al. (2014) also confirmed that wet tillage in rice farming leads to soil physical deterioration. The effects of tillage and puddling on soil physical properties are strongly determined by soil texture, type of clay minerals, soil structure, and the content of soil organic matter and sesquioxides.

The presence of a hardpan helps to reduce water losses and limits plant nutrient leaching through percolation (Sanchez, 1973; De Datta and Karim, 1974; Reddy and Hukkeri, 1980). It is also an obstacle for root penetration to utilize the nutrients in subsoil layers and hence leads to poor standing condition for the rice crop if the compacted layers are located at a shallower than the normal rooting depth (De Datta and Barker, 1978; Greenland, 1985; Khan, 1996). In general, bulk density and soil strength of the hardpan are negatively correlated with growth and grain yield of rice (Sharma and Datta, 1985b; Hussain et al., 1999; Wickramasinghe, 2011). Accordingly, the depth and degree of compaction has become an obstacle for the deeper rooting systems of upland crops such as maize, beans or other crops in rotation with flood irrigated rice (Lima et al., 2002).

1.2.4 Intensive rice production and its effect on greenhouse gas emissions and soil chemical properties

In submerged and puddled soil, gas exchange between atmosphere and soil is severely restricted. Soil submergence causes a decline in soil oxygen concentration and an increase in carbon dioxide concentration, due to respiration of rice roots and soil biota. However, the normal concentration of CO_2 in submerged soil is usually non-toxic to rice growth. Rice has aerenchyma cells which transports O_2 from leaves to roots for root respiration (Jackson and Armstrong, 1999; Colmer, 2003). But in the case that the soil receives a high amount of easily decomposable organic matter, the CO_2 level may become toxic. Additional disadvantages, moreover, are also intrinsic to paddy rice cultivation, such as potential pollution hazards for water and air, because more rice crops per year can result in heavier pesticide use (Nhan et al., 2002). Literature shows that, in countries with a high chemical fertilizer use, paddy fields are considered to be the largest potential non-point source of pollutants for water bodies, particularly nitrogen and phosphorus (Kyuma, 2005). Globally, flooded paddy fields are the major source of methane emission (Neue et al., 1990). Paddy soils are reported to be responsible for ~11% of total annual methane emissions (Smith et al., 2007; Forster et al., 2007; Tokida et al., 2011). This methane escapes into the atmosphere and contributes to global warming (Maclean et al., 2002; FAO, 2004). According to Kyuma (2005) it is imperative that paddy rice researchers strive to lessen these local as well as global environmental hazards incurred by paddy rice cultivation.

In paddy soils, timing of crop residue incorporation and microbial mediated redox processes control the soil organic carbon dynamics, which are related to the microbial accessibility of carbon (Kader et al., 2013) and hence affect soil physical properties such as soil structure and soil porosity. Low rates of soil organic matter decomposition and nitrogen mineralization in poorly drained rice fields have been observed and are associated with anaerobic soil conditions (Sahrawat, 2004). Previous studies on tropical paddy soil have shown that long term rice cultivation may increase soil organic matter (Zhang and He, 2004); the soil organic matter content can be increased by input of residual root mass, even if all of the aboveground biomass is removed at harvest (Sahrawat, 2004; Pampolino et al., 2008).

In triple rice crop systems, fallow periods between crop seasons are short, the paddy soil is not allowed to dry and re-oxidize completely. Moreover, large amounts of rice crop residues are returned to the field three times per year. It is hence likely those years of intensive cropping lead to a decline in the steady-state soil redox potential along with a gradual accumulation of reduced substances (iron and organic compounds). Consequently, there is a change in qualitative composition of soil organic carbon toward more phenolic compounds (Kader, 2012). These changes may largely influence the biochemical composition of soil organic matter and accordingly organic nitrogen. Indeed, Olk et al. (1996) reported that rice yield is reduced by a decrease in the indigenous nitrogen supply resulting from a change in the chemical properties of soil organic matter owing to continuous flooding, but not by a decrease in soil organic matter and total soil nitrogen. Furthermore, intensive cultivation of two and three irrigated rice crops per year with the corresponding submergence of soil can promote a buildup of less decomposed substances, which becomes incorporated into young soil organic matter fractions. This has been associated with reduced nitrogen supplying capacity of rice soils (Olk et al., 1996, 2000) and adversely impacting the sustainability of rice production (Schmidt-Rohr et al., 2004). Furthermore, Olk et al. (2007) also stated that anaerobic decomposition of crop residues in rice rotations inhibit nitrogen mineralization compared to aerated decomposition. They suggested increasing incorporation of crop residues during the non-submerged period in lowland paddy fields, enabling aerobic decomposition of residues to improve the soil nitrogen supply. Low redox potentials in flooded rice soils also affect the state of micronutrients such as iron (Fe) and manganese (Mn). In the case of iron, insoluble ferric iron (Fe^{3+}) is reduced to plant available but easily leachable ferrous iron (Fe^{2+}) through microbial action (Neue and Scharpeseel, 1984).

Dobermann and Fairhurst (2000) stated that in intensive rice monoculture systems, the recycling of rice straw has a major positive influence on the potassium and silicon balance and on the maintenance of soil potassium and silicon status. This straw recycling could also reduce total nitrogen fertilizer requirements (Cassman et al., 1998). In South Asia, however, large amounts of rice straw are often removed from the field or burned to facilitate fast and easy land preparation. Hence a negative potassium balance is becoming prominent. Dobermann et al. (1995) provided data from 11 sites in China, India, Indonesia and Vietnam; most of these showed a negative net potassium balance. Dobermann and Witt (2000) observed that about 80% of intensive rice fields in Asia have a negative potassium input-output balance, with an average of about -26 kg K ha^{-1} $crop^{-1}$. Si balances are also often negative (-150 to -350 kg Si ha^{-1} $crop^{-1}$) in intensive rice systems because application of Si is not common and rice straw is removed (Dobermann and Witt, 2000). Moreover, continuous intensive rice cropping promotes high levels of nutrient extraction from soils without natural replenishment hence causing soil nutrient deficiency (Cassman et al., 1995).

Promotion of crop pests, increased disease pressure and the potential build up of soil pathogen populations due to long-term intensive monoculture (Sumner and Boosalis, 1981) are also constraints to sustaining high yield in intensive rice systems. Nhan et al. (2002) reported that in triple rice cropping farmers applied two times more herbicides and insecticides and three times more fungicides than in double rice cropping.

Besides its negative effect, growing rice in submerged soil has a great ameliorative effect on chemical fertility such as higher natural supply of bases and silica, higher phosphorus availability, detoxification of excessive nutrients and agrochemicals, relative ease of weeding, and carbon sequestration (Dobermann and Witt, 2000; Kyuma 2004). Further, the constant submergence also influences soil pH. The important change upon submerging a soil is bringing soil pH into the neutral range. Sahrawat (2005) showed that in the redox reaction ferric iron (from amorphous ferric hydroxides) serves as an electron acceptor and organic matter (CH_2O) as the electron donor. This reaction results in the neutralization of acidity and increase in pH:

$$Fe_2O_3 + 1/2CH_2O + 4H^+ \rightarrow 2Fe^{2+} + 5/2H_2O + 1/2O_2 \qquad (1)$$

However, as discussed by Sahrawat (2005) a decrease in pH for alkali or calcareous soils is the result of accumulation of carbon dioxide in flooded soil, which helps in neutralizing alkalinity:

$$CO_2 + H_2O \rightarrow H_2CO_3 \qquad (2)$$

$$H_2CO_3 \rightarrow H^+ + HCO_3^- \qquad (3)$$

Overall, the rice yield potential is usually determined only by varietal characteristics and the seasonal pattern of environmental variables such as temperature and radiation (e.g., Kropff et al., 1994). However, attainable yield is generally considerably lower, because for part or even all of the growing season, rice growth is restricted by shortages of water and/or nutrients (Rabbinge, 1993), soil constraints (Casanova et al., 1999) or other factors such as diseases, pests and weeds. Comparative analysis shows that the efficiency of fertilizer and pesticide investments is lower in triple-cropped rice than in double-cropped rice. These findings imply that rice intensification with more crops per year and higher agro-chemical investments are not the best economic option (UNEP, 2005). This economic disincentive is progressively worsening because declining soil resources and increasing labor cost has threatened the sustainability of conventional rice production systems.

1.3 Rice-upland crop rotation as solution for soil resources conservation

Soil quality is best defined in relation to the functions that soils perform in natural and agroecosystems. The quality of soil resources has historically been closely related to soil productivity (Hillel, 1991), although nowadays the concept of soil quality has been extended and relates now to the capacity of soil to function in support of the important ecosystem services needed to sustain productivity and maintain environmental quality (Karlen et al., 2001). The physical, chemical and biological characteristics of different soils vary a great deal, so that different soils are suited to different uses. Where a soil’s characteristic match those needed for its current use, we can say that soil is of good quality. The measure of quality thus relates to several aspects of a soil: its chemical condition, i.e., its fertility including the amount of humus (organic matter); its physical condition, for example, whether it has become compacted; and its biological condition, i.e., whether it contains beneficial soil life, such as bacteria and earthworms.

The soil conditions required to sustain rice growth differ from those required by upland crops. Indeed, soil is puddled before rice sowing and kept flooded to create anaerobic conditions for rice growth. Contrariwise, upland crops are grown in well-drained soils under aerobic conditions. Puddling creates a plow layer that reduces water percolation losses and enhances the water and nutrient use efficiency of rice (Mousavi et al., 2009). However, puddling deteriorates soil physical properties forming hardpans at shallow depth that are conceived to have negative effects on the following upland crop (Gathala et al., 2011) and potentially on the following rice crop. To mitigate negative effects on soil quality of the present cultivation practices inherent to intensive mono culture rice, rice rotation with upland crops has been proposed. In fact, crop rotation in rice monoculture systems is a feasible alternative strategy to control unfavorable aspects, diversifying agricultural production and improving soil characteristics as well (Lima et al., 2002). The rice-upland crop rotation is the most important agricultural production system in India, China, Bangladesh (Timsina and Connor, 2001), especially the rice-wheat rotation system (Fan et al., 2008).

Rice-upland rotation could change the soil properties of long-term flooded paddy. The positive effect of crop rotation on the soil bacterial community structure and rice yield has recently been reported by Xuan et al. (2012). Other studies evaluating long-term crop residue additions with various tillage treatments have shown favorable modification of soil physical properties in typical rice soils (Bhagat et al., 1994; Sharma et al., 1995; Mohanty et al., 2007). It is now evident that crop rotation increases yield and that this practice promotes sustainable agriculture (Mandal et al., 2014; Filizadeh et al., 2007), because excessive and unnecessary tillage and puddling operations are limited in upland crop season(s). Accordingly, physical properties of long-term flooded paddy soil such as soil structure and capillary porosity can be changed by the rice-upland crop rotation practice (Zhou et al., 2014).

Rotation of upland crops and rice with its flooded soils brings a transition in soil aeration status from anaerobic to aerobic and back to anaerobic. The frequent cycling between anaerobic and aerobic condition results in a greater rate of soil organic carbon decomposition (Xu et al., 2007; Motschenbacher et al., 2011). A positive balance of soil organic carbon in rice-upland crop-rice rotation compared to rice-fallow-rice systems was recently highlighted by Mandal et al. (2014). This has impact on the accumulation or dissipation of soil mineral nitrogen, phosphorus availability and potassium exchangeability (George et al., 2002). Kumar et al. (2005) also reported higher sustainability of rice-maize cropping systems irrespective of variations in weather and price.

Furthermore, water requirements in lowland rice are generally high (Bouman et al., 2007); rice crop rotation with upland crops could also save water. For instance, conventional rice production requires 3,000 to 5,000 lit of water to produce one kilogram of rice (Belder et al., 2004; Geethalakshmi et al., 2011), which is 2-3 times more than other cereal crops such as maize, barley, wheat and sorghum

(Barker et al., 1998; Bouman et al., 2007; Tuong et al., 2005). Site-specific conditions can dictate a wide variation in the total water use (irrigation + rainfall), ranging from 400 mm for heavy-textured soil to more than 3,000 mm for coarse-textured soil (Bouman and Tuong, 2001; Cabangon et al., 2004). Tabbal et al. (2002) reported as high as 3,500 mm of water input in paddy fields in Philippines. Moreover, Garg et al. (2009) reported that the total water input in irrigated lowland rice in the red laterite soils of eastern India during the wet season may be as high as 6,000 mm.

Crop rotation is one of the essential practices in sustainable agriculture systems, because of its effects on soil fertility and other benefits including a reduction in pest competition such as weeds (Blackshaw et al., 1994; Filizadeh et al., 2007). However, the effect of cultivation and management on some soil properties such as soil bulk density has not been consistently observed. Variation in soil bulk density among rice-upland crop rotation sites may be due to different soil types, soil texture and cultivation and management practices. Wang et al. (2003) observed that in a 10-year experiment of rice-upland crop rotation, bulk density was 23.4% higher than that of the continuous rice culture at 0-10 cm depth. On the other hand, Motschenbacher et al. (2011) stated that soil bulk density differed among common rice-based cropping systems with corn, soybean and winter wheat, but few consistent trends were evident.

However, we would also acknowledge the reasons why farmers like doing double-cropped or even triple-cropped rice, i.e., familiarity with farming practices due to presence of local rice markets, and no need to buy twice the farm machinery to cultivate two different crops. Alternatively, in the area where compaction is not too severe, or is relatively shallow, there are other options for rice farmers besides crop rotation such as aerobic incorporation and especially wetting/drying cycles during the season. This farming practice saves water, reduces diseases, might inhibit arsenic uptake into the grain (Xu et al., 2008; Norton et al., 2012), and minimizes greenhouse gas emissions, while possibly introducing more aerobic conditions into the soil. Interest is growing rapidly in wetting/drying cycles in both Asia and the US. (Zhang et al., 2009; Yang et al., 2009; Adhya et al., 2014).

1.4 The Vietnamese Mekong Delta

1.4.1 Geographic position and biophysical conditions

The Vietnamese Mekong Delta is a young delta that covers an area of ~40,000 km^2 and has a total population of ~18 million (~20% of the country’s population). It is an important agricultural region located in the southern part of Vietnam spreading from 11^{o}00’ to 8^{o}30’ N latitude and 104^{o}10’ to 107^{o}10’ E longitude with three sides surrounded by sea. It is bound on the north by Cambodia, on the east and south by the East Sea and on the west by the Gulf of Thailand (Fig 1.1).

Figure 1. 1 Map of the Mekong Delta in Vietnam. The different colours refer to province boundary

The delta is mainly influenced by a tropical monsoon climate. It is characterized by two distinct seasons: a dry and a rainy season (Sam, 1996). The dry season starts in December and ends in May with a rainfall of about 10% of the total annual amount with north-eastern wind direction. The rainy season starts in Jun and ends in November with about 90% of the annual rainfall with south-western wind direction. There are 110-170 rainy days annually and mean annual rainfall is ~1,600 mm. The average monthly temperature varies between 25 ^{o}C and 28 ^{o}C. During the warmest months (March to April) the mean temperature is 32 to 33 ^{o}C and during the coolest months (December to January), it is 23 to 25^{o}C (Phong, 1986). Most agro-climatological factors in the Mekong Delta are favorable for agricultural production all year round. Generally, the average elevation of the Mekong Delta is about 2 m and almost flat (Thao, 1986, 1997).

The cultivated area amounts to 2.79 million ha which is 71.6% of the total land area of the region. Rice (*Oryza sativa* L.) is the main crop and essential for national food security with more than 90% of the cultivated area being used for rice production. It is cultivated in a very intensive way with two or three crop seasons per year depending on the ecological condition of each region (Sanh et al., 1998), and in some regions up to seven rice crops are cultivated over two years (Dobermann et al., 2004).

Nowadays, the Mekong Delta is the largest grain producing area in Vietnam. It plays a very important role in the social-economic development strategy of Vietnam and is a key element for food security of the country as more than ninety million people depends on rice for their dietary requirements. The region contributes to ~50% of the national agriculture produce. It contributes more than 33% of the total gross output of the country’s agriculture while its area only accounts for 12% of the total natural land area of Vietnam (General Statistics Office, 2012). With an annual production of more than 20 million tons of rice, the delta has been considered as the “rice basket” for the whole country accounting for 54% of national rice production (General Statistics Office, 2012). It has been the biggest rice growing area in Vietnam and a major rice growing region in Southeast Asia. The Mekong Delta produces rice not only for domestic consumption but also for export and it accounts for 90% of the national rice export volume (Duong et al., 2005).

The Mekong Delta is a typical peninsular land of Vietnam. It is a young delta deposited by a river and creek network systems, about 6,000 years ago (Khoa, 2002). The soils in the Mekong Delta are controlled by three main distributing processes: the process of transportation and alluvium of sediments by the Mekong river forms the typical shape of the new alluvial plain in the center of the Mekong Delta; the process of forming old swamps forms the large areas of acid sulphate soils; and the process of forming the coastal plain forms the saline soil belt in the Mekong Delta (Hien, 2001). Ninety percent of the total area of the Vietnamese Mekong Delta (approximately 3.6 million ha) is lowland. Chieu et al. (1990), and Ve and Anh (1990) divided soils in the Mekong Delta into major groups, locally described as alluvial soils, acid sulfate soils, saline soils, grey soils, peaty soils and sandy soils. According to international classification, these soils are respectively Fluvisols, Thionic Gleysols, Salic Gleysols, Acrisols, Histosols and Arenosols. Nowadays, soils in the Mekong Delta are classified into nine major soil groups (Fig 1.2): Fluvisols, Proto-Thionic Gleysols, Ortho-Thionic Gleysols, Salic Gleysols, Acrisols, Histosols, Arenosols, Plinthosols, Leptosols (Soil Science Department - Can Tho University, 2015).

Among major soil groups, Fluvisols is the most important, covering the largest area with 31% of the Mekong Delta. They are concentrated along the banks on both sides of the Mekong River and occur in the central part of the delta. The natural low water permeability caused by a compacted B horizon makes these soils well suitable for irrigated rice production. The soils have a silty clay to clay texture. Soil organic carbon content of paddy soil in the Mekong Delta is generally high (Dobermann et al., 2002; National Institute for Soils and Fertilizers and Department of Science Technology and Product Quality Vietnam, 2002). Kyuma (1985) reported that the average total carbon concentration of the soil in the Mekong Delta was 2.5%. The total nitrogen ranged from 0.1 to 0.25%, and phosphorus and potassium are of medium level (Estelles et al., 2002).

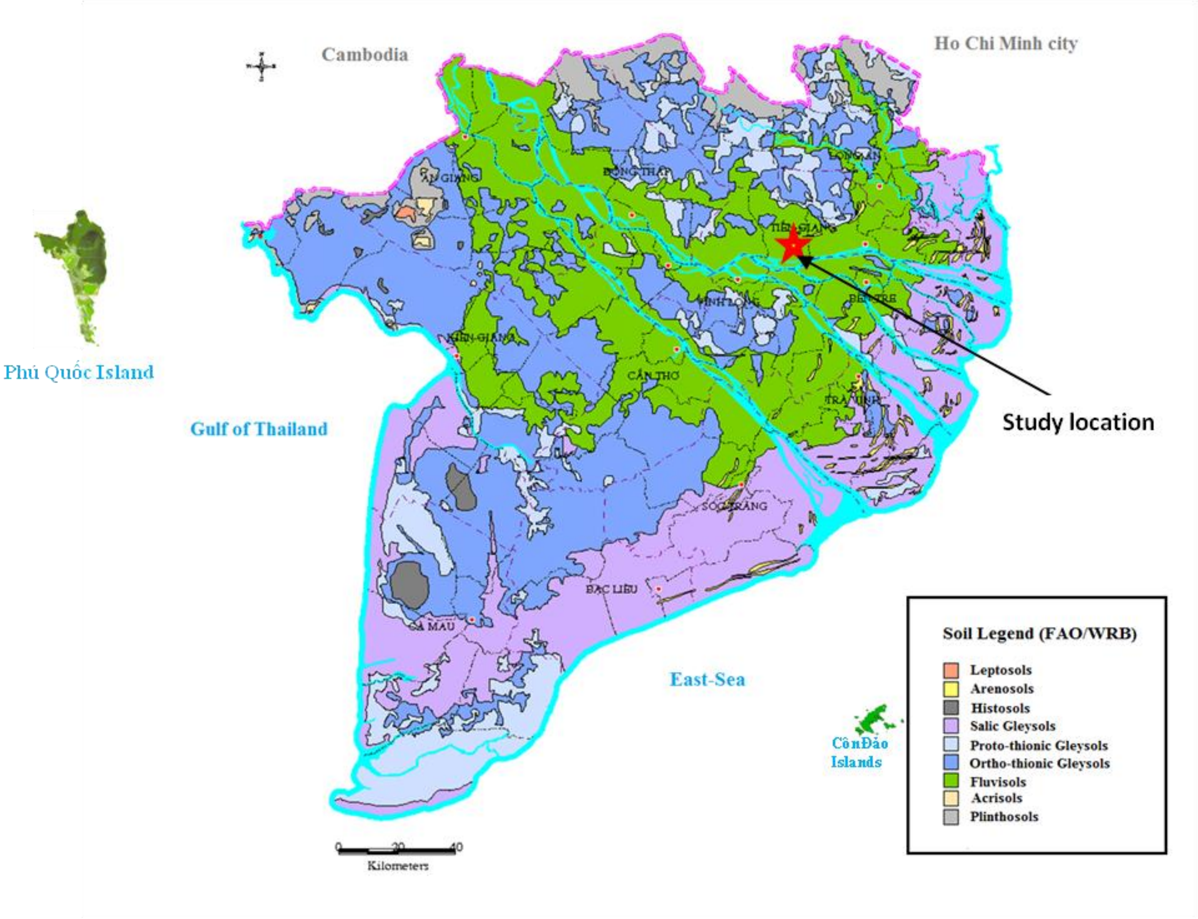


Figure 1. 2 Soil map in the Mekong Delta (Source: Soil Science Department, Can Tho University)

1.4.2 Agricultural challenges of rice cropping in the Mekong Delta

Originally, the Mekong Delta was covered by forest. They were reclaimed and exploited for agricultural production from the start of the 17th century, and gradually cultivated by applying various agricultural practices including building of dikes and irrigation canals, plowing among others, focusing on paddy rice cultivation (Lua, 1987). In the middle of the 19th century, the Mekong Delta had become the largest region for agricultural production of Vietnam, essentially rice production for commercial purposes.

In the past, tillage was based on the use of human and animal power. Since 1980s, modernization in agriculture has resulted in a system of continuous intensive monoculture with mechanical practices. Indeed, the system with three rice crops per year was using a heavy four-wheel tractor, with plowing to a depth of ~20 cm.

From 2000 onwards, shallow soil preparation is the common method adopted by most farmers with handheld two-wheel tractor for initial soil preparation. The most common soil preparation practices in the Mekong Delta are tillage and puddling under wet conditions followed by broadcasting rice seedlings into the puddled paddy field and growing the rice crop in a submerged condition. After decades, the ultimate result of this practice was the development of a plow pan close to soil surface. This land use system has mainly enlarged in the past 20 years with short duration (90-100 days) and high yielding varieties on the areas along the Mekong River. This shift in cropping pattern has brought about some additional chemical fertilizer, pesticide and insecticide inputs as well as longer inundation periods throughout the year with anaerobic soil conditions.

Nowadays, continuous paddy rice cultivation is the major cropping pattern in the Mekong Delta of Vietnam (Thinh, 2009). The present intensive continuous monoculture system with three rice crop per year aims at maximizing paddy rice production. At harvest, the rice straw is burned or removed for mushroom cultivation or cattle feed (Watanabe et al., 2009).

Despite their high agricultural potential, the productivity of paddy soils in the Mekong Delta tends to decrease in past years, especially in high intensive rice cultivation areas. In the period 1995-1999, rice yield decreased with 12% in winter-spring and summer-autum season and with 21% in spring-summer season, as a result of increased intensive farming with poor soil management (Khoa, 2002). Particularly, changes in the land preparation pattern in paddy cultivation during the last two decades would be one of the major reasons for the depletion of soil productivity. Soil fertility for sustainable rice cultivation in the Mekong Delta seems to be under threat by these reasons. Farmers began to use fertilizer at higher rates than those recommended to maintain rice yield (Khoa, 2002; Guong et al., 2010b). As a consequence, fertilizer use already reached a high level and further increases are not likely to be profitable. Among the numbers of possible causes for the stagnation and decline of rice yield nutrient deficiency and deterioration of soil physical properties, i.e. the formation of a shallow plow pan and continuous anaerobic conditions, have been suggested as major ones (Cassman et al., 1995; Khoa, 2002). Moreover, some symptoms of declining soil productivity were mentioned by farmers. The symptoms were low fertilizer response, soils becoming compacted, limited root penetration, falling down of rice after flowering, and frequent outbreaks of insects and diseases, which lead to increase in production cost. On average, total production costs increase at a rate of 2-2.4% per year in the period 1995-2004 (Khiem and Khai, 2008). As a result, farmers' income in the intensive triple rice cropping in the Mekong Delta likely falls.

A preliminary study conducted in intensive rice monoculture areas prompted following assumption. As a result of intensification of rice cultivation in the Mekong Delta, the plow layer became shallower and it disturbs the growth of rice root that is necessary for good rice yield. Khoa (2002) and Phuong (2006) reported that the compacted layer depth of those rice fields varied from 10-25 cm and the thickness varied from 20-50 cm, mainly originated from rice monoculture with high soil rotation, increased mechanization in wet tillage and illuviation process of fine particles. The plow pan is moderately hard when saturated. In general, rice has a considerably compact and shallow root system compared with other crops. The majority of rice roots penetrate to a depth of about 20-25 cm (Sharma et al., 1994). Rice roots do not generally grow over 30 cm depth (Jaquie et al., 2012) and seldom exceed a depth of 40 cm in continuously flooded fields (IRRI, 1997). However, presence of a shallow plow pan may restrict the root growth, which may reduce the nutrient uptake by the plant and hence reduce biomass and grain yield. If reasonable and affordable solutions will not be given, rice yield in the Mekong Delta will continue to decline in near future. This is emergent and we need to develop strategies on how to conserve paddy soil. Although crop rotation systems have been studied by many researchers, extensive investigation and research on their long-term impact on soil quality and crop parameters, their practicability, economic feasibility and farmer acceptance is still need and should be considered for particular regions of interest with differences in ecological condition.

There is no single agronomic practice that resolves the soil compaction problem in paddy soil. Rather, a combination of practices should be suggested to mitigate the problem. These practices include minimum tillage, loosening compacted soil by deep ripping and using a crop rotation which includes deep and strong rooting plants able to penetrate relatively compacted soil. In order to develop sustainable rice crop production systems, an experiment was set up in 2002 with three new cropping systems with rotations of rice and upland crops were introduced beside intensive rice monoculture system on paddy alluvial clayey soil in Cai Lay district, Tien Giang province, the most suitable region for rice production in the Mekong Delta. Maize and mung bean were grown in rotation with rice. Intensive rice monoculture, the common practice adopted by farmer was used as a control treatment. Comparative field studies under controlled conditions are required to evaluate the impact of new cropping systems on soil quality and yield.

Previous studies by Guong et al. (2010a, b) in this experiment field demonstrated that the rotation of rice with upland crops resulted in significantly greater contents of soil mobile humic acid (MHA), labile organic nitrogen, nitrogen mineralization and soil available nitrogen supplying capacity compared with intensive rice monoculture systems. In addition, using labeled urea fertilizer (^{15}N) to discriminate soil-N from fertilizer-N taken up by rice showed that there was more soil mineral nitrogen taken up in rotation systems compared to rice monoculture system (Guong et al., 2010a). On the other hand, the study of Xuan et al. (2012) conducted at the same experimental site, showed that rice rotated with maize or mung bean provides equilibrium in the soil microbial environment. Composition, abundance and diversity of soil bacterial communities in the crop rotation systems were significantly different and higher than those in the rice monoculture system, which may promote rice growth and productivity. Moreover, in the same field experiment, Dung et al., (2010) reported a positive effect of rice-upland crop rotation on the composition of the microbial community colonizing in rice straw residues. The abundance and diversity of soil microorganisms therefore may increases the availability of plant nutrient elements (Turmuktini et al., 2012). In another experimental set up on paddy rice field with alluvial soils at Chau Thanh district, Hau Giang province, Hung et al. (2005) reported that the nitrogen fertilizer use efficiency was higher in case of rice-sweet potato and rice-soybean rotation compared to the continuous rice monoculture system.

In the Mekong Delta, the effects of crop rotation on soil quality in paddy fields have been reported by several studies, but they are just focusing on the chemical and biological aspects of soil fertility. In clay soils which are cultivated under wet conditions and are puddled for rice cultivation, the presence of a plow pan may influence soil physical properties, but also affect soil chemical properties and nutrient availability. Generally, an important factor for sustainable productivity of tropical soils is maintenance of soil physical characteristics at an optimum level (Lal, 1974). Singh and Singh (1996) mentioned that tillage levels and soil physical conditions modify the root systems. When this is achieved, the productivity of these soils can be substantially improved by the use of fertilizers. Since the nature of soil physical properties were generally of little concern during rice crop-growing seasons due to the flooded-soil conditions, the impact of long-term crop rotation on physical properties in the Mekong Delta was not investigated.

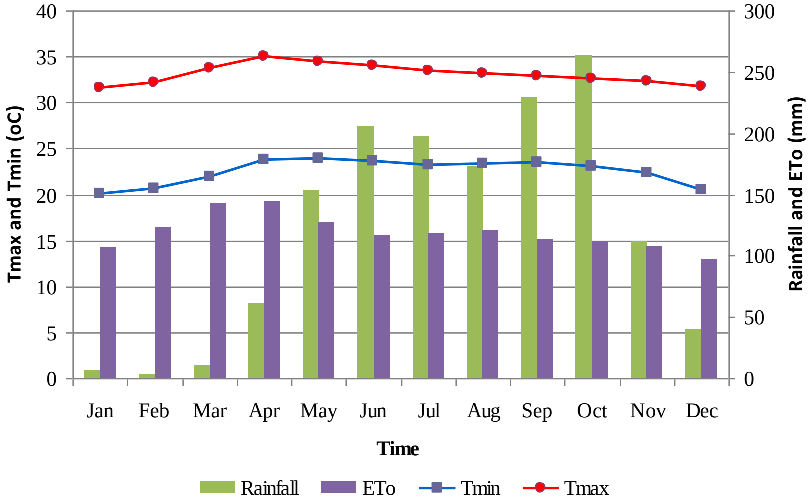
Considering the above facts, an understanding of the relationship among long-term crop rotation, soil physical properties, root growth, soil nutrient stock and rice yield in paddy rice cultivation is essential. Therefore, evaluation of soil physical and chemical characteristics related to soil degradation and rice production decline is very important and necessary to study. In this study, we examined whether the intermittent cultivation of one or two upland crops in a paddy rice cultivation system (resulting in alternate anaerobic-aerobic conditions), without flooding conditions and puddling in upland crop season(s), results in important changes in soil physical and chemical properties compared to systems which undergo continuous paddy rice cultivation (continuous anaerobic conditions).

1.5 Characteristics of the study location and field experiment set up

The study area is located in the northern part of the Mekong River, the major and representative region for the current problems associated with long-term intensive rice monoculture systems in the Mekong Delta. A field experiment was performed from 2002 to 2012 in a previously intensive irrigated paddy rice field in which farmers harvested three rice crops from the same field each year at Cai Lay district, Tien Giang province (at ~10°22’ North latitude and 106°07’ East longitude). The study site had a flat topography (0.5-1%) and an elevation of 2 m above sea level. Long-term experiments are vital for testing the sustainability of new cropping systems and they enable the direct quantification of changes in soil properties resulting from changed cropping system practices.

The land was used to produce one traditional rice crop per year before 1960. This traditional rice crop had a long growing period of 5 to 6 months. Gradually, high yield rice varieties were used and two rice crops per year, a winter - spring crop and summer - autumn crop were cultivated. Since 1980, three rice crops are cultivated: winter - spring (November to January), spring - summer (March to May), and summer - autumn (July to September) with short growing periods of 90-95 days.

The climate of the experimental area is tropical, wet and humid. Heavy rainfall occurs during the monsoon and is scare at other times. The monthly average climatic characteristics near the experimental field for the period from 1991 to 2010 indicate that the total annual evapotranspiration was around 1,400 mm. The mean annual rainfall was above 1,500 mm of which 80% fell during the summer-autumn seasons, that is, from the middle of May to the end of October. From November to April, rainfall was less than 20% to the annual rainfall. The period from January to March received virtually no rain (Fig. 1.3). The relative humidity ranged from 80 to 85%. The temperatures were always between 20 and 35^{o}C; from mid-March to late June, the maximum and minimum temperatures were in the highest range whereas from mid November onward up to mid-February temperature was in the minimum range. However, the highest maximum temperature was recorded in April. These climatic factors are favorable for agriculture and tropical crops growth, especially for rice, maize, mung bean and other upland crops (Sys et al., 1993).



Tmax: maximum temperature, Tmin: minimum temperature, ET_0: reference evapotranspiration

Figure 1. 3 Distribution of mean monthly rainfall, temperature and evapotranspiration from 1991 to 2010 at the experimental site (Cai Lay district, Tien Giang province, at ~10°22' North latitude and 106°07' East longitude).

The soil at the field site was classified as Gleyic Fluvisols (IUSS Working Group WRB, 2015) or Typic Fluvaquent (Soil Survey Staff, 2010) (Soil Science Department - Can Tho University, 2015). The principle soil characteristics at the experimental site are shown in Table 1.1. The textural class was clay and the soil had a pH of 5.4-5.5, EC of 0.26-0.32 dS m^{-1}, SOC of 1.02-2.15 %, CEC of 23-24 cmol(+) kg^{-1}, and bulk density of 0.95-1.36 Mg m^{-3}. Visual inspection of soil profiles and measurements with a penetrologger (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) showed that a plow pan was present at a depth of about 15 cm from the surface with a thickness of ~30 cm. Clay mineralogy was not determined but is mostly dominated by smectites and muscovite in the study area (Khoa, 2002). The soil in the study location does not show strong expansivity.

Table 1. 1 ***Soil characteristics of the experiment field prior to the experiment***

Depth (cm)	Sand^{a} (%)	Silt (%)	Clay (%)	ρ_b ^{b} (Mg m^{-3})	pH$_{(H2O)}$	EC^{c} (dS m^{-1})	SOC (%)	CEC^{d} (cmol+ kg^{-1})
0-20	1.9	32.0	66.1	0.95	5.5	0.32	2.15	24.5
20-40	1.1	31.2	67.7	1.36	5.4	0.26	1.02	23.1

^{a}Sand: 50–2000µm, Silt: 2–50µm, Clay: <2µm, $^{b}\rho_b$: Bulk density, ^{c}EC: electric conductivity, SOC: soil organic carbon, ^{d}CEC: cation exchange capacity.

The field experiment was laid out as a Randomized Complete Block Design. The treatments consisted of four cropping systems with four replications. Each plot covered an area of 42 m^{2}. Between plots, distances of 0.3 m were kept and between replicates the distance was 1 m. The main crop rice (*Oryza sativa* L.) was rotated with maize (*Zea mays* L.) and mung bean (*Vigna radiate* (L.) R. Wilczek) in different combinations with three crops per year. Figure 1.4 shows the schedule according to which the different crops were seeded and harvested. The four applied rotation systems were:

(1) rice (crop 1) – rice (crop 2) – rice (crop 3) (designated as R-R-R),
(2) rice (crop 1) – maize (crop 2) - rice (crop 3) (designated as R-M-R),
(3) rice (crop 1) – mung bean (crop 2) - rice (crop 3) (designated as R-Mb-R),
(4) rice (crop 1) - mung bean (crop 2) - maize (crop 3) (designated as R-Mb-M).

The winter-spring season (WS) (November-February) is considered as the first season in the rotation system, with rice being cultivated for all four treatments. In the following spring-summer season (SS) (March-June) and summer-autumn (SA) (July-October), different crops can be cultivated (Fig 1.4). These crop rotations were repeated every year during ten years of experiment.

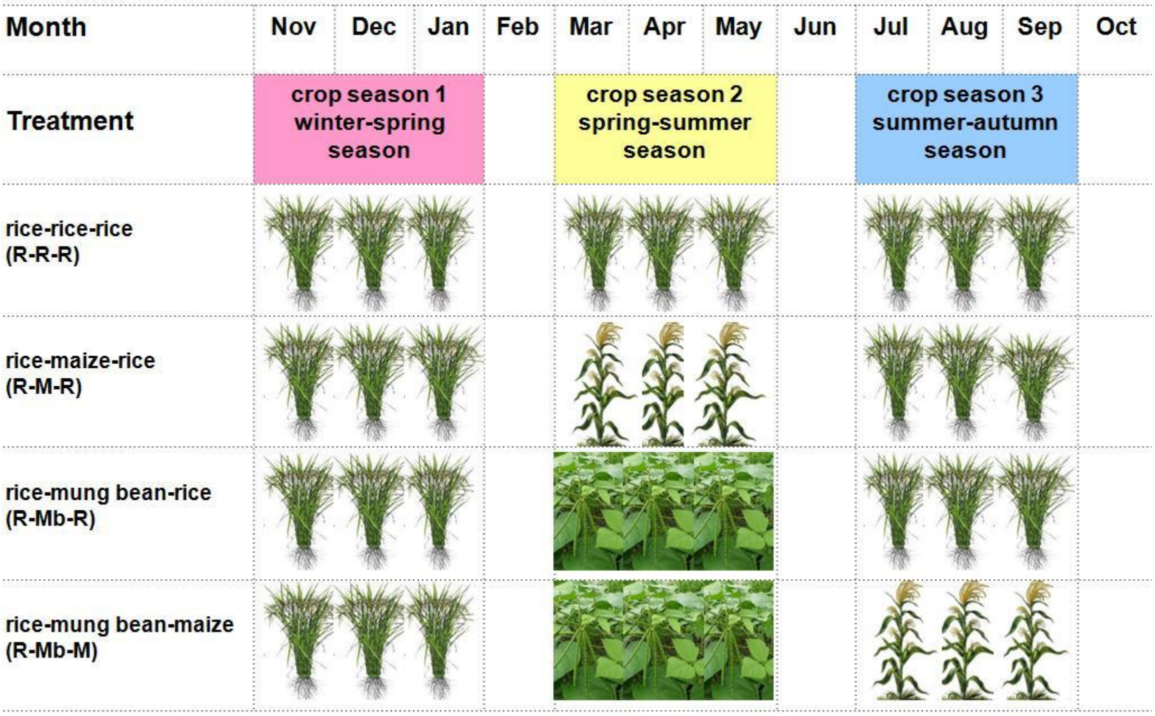


Figure 1. 4 Yearly crop rotation in long-term field experiment (2002-2012)

Prior to establishment of the experiment, the field had been conventionally cropped with intensive rice monoculture for over 30 years. In the study area, as well as in our study, rice crops are cultivated with short growing varieties (90 to 95 days) belonging to the tropical *Indica* varieties group (Keyan et al., 2011).

The fertilizer doses for rice, maize and mung bean were 100N-45P_2O_5-30K_2O, 140N-50P_2O_5-30K_2O, 40N-30P_2O_5-60K_2O kg ha^{-1}, respectively based on recommendations by the Department of Soil Science, Can Tho University. The fertilizer doses are repeated for each crop cycle in the experiment. Fertilizers used for the experiment were urea (46% N), super phosphate (13.5% P_2O_5) and potassium chloride (60% K_2O).

Soil preparation was done around 1-3 days before sowing. For rice cropping, this was done by chisel tillage (10-15 cm depth) followed by puddling with the aim of preparing a seedbed of fine aggregates. This was often complemented with a pass of a special leveler made by heavy wood, to smoothen and level the puddled surface layer. As is typical in the area, before the year 2000, the type of implement was a heavy four-wheel tractor, whereas from 2000 onwards, it was a handheld two-wheel tractor. For soil preparation under maize and mung bean, beds of 20 cm height above the field surface and 40 cm width were manually prepared with a hoe (Fig. 1.5). This resulted in turning the soil between the top soil and compacted layer, creating 30 cm deep furrows to drain extra water. The position of furrows is changed every upland crop season to assure that the compacted layer is loosened anywhere in the experiment plots. When maize or mung bean cultivation was followed by rice, the soil was leveled again. The respective soil preparation was repeated prior to each growing season. The rice field plots were irrigated when 100–150 mm of standing water dropped below the soil surface throughout the rice cropping season till ten days prior to harvest.

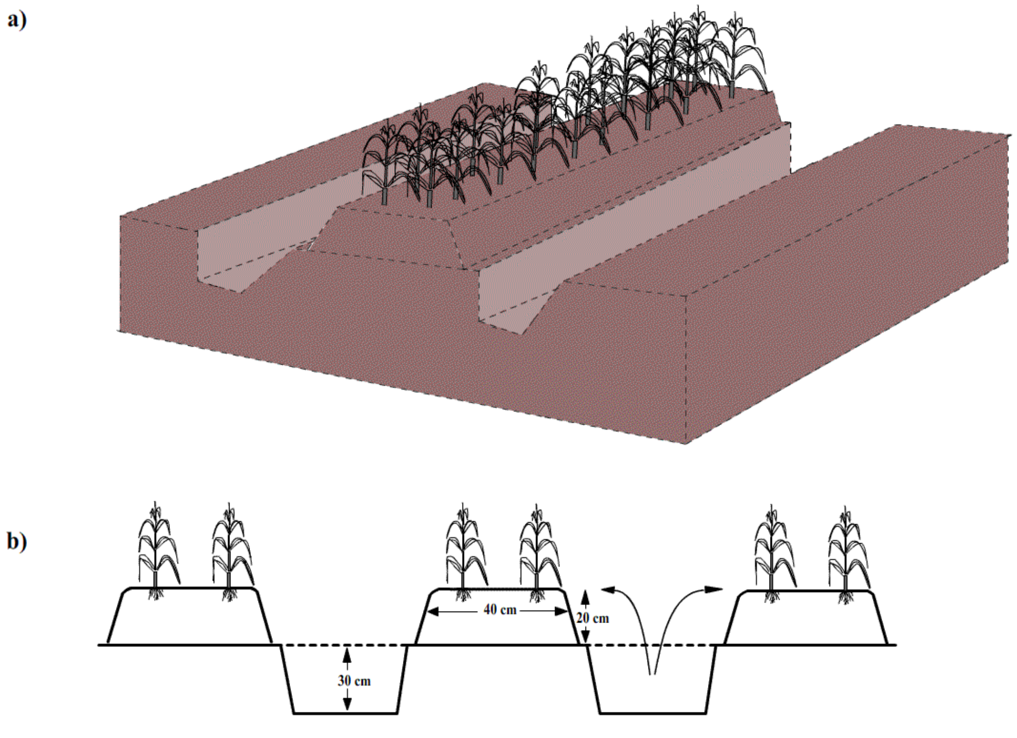


Figure 1. 5 Soil preparation methods for maize and mung bean

In addition, a farm household sampling was undertaken in four villages (Long Khanh, Cam Son, Binh Phu, Long Tien) around experimental site. All villages included four types of crop cultivation: three rice crops per year (RRR), three upland crops per year (UUU), one rice crop and two upland crops per year (RUU), and two rice crops and one upland crop per year (RUR) (Table 1.2). In total 40 fields (one type of cropping system for one farmer field) were identified based on randomness for soil sampling: 10 farmer fields were sampled for each cropping system. At the time of soil sampling, RUR, RUU and UUU fields had been under that cropping system for five years, whereas RRR fields had been cultivated as such for more than 30 years. All the soil samples were taken in the dry season after harvest of rice (RRR, RUR and RUU) or upland crops (UUU).

Table 1. 2 ***Cropping systems in the study area***

Cropping system	Cropping season		
	Late wet	Dry	Wet
Rice–Rice–Rice (RRR)	Rice	Rice	Rice
Rice–Upland crop–Rice (RUR)	Rice	Upland crop	Rice
Rice– Upland crop– Upland crop (RUU)	Rice	Upland crop	Upland crop
Upland crop–Upland crop–Upland crop (UUU)	Upland crop	Upland crop	Upland crop

Rice is planted with a conventional flooding system on flat fields after plowing, puddling and leveling the top 10 cm under wet conditions with a small tractor before sowing. Upland crops (cucumber – *Cucumis sativus,* tomato – *Solanum lycopersicum*, maize – *Zea mays*, chili pepper – *Capsicum annuum*, okra – *Abelmoschus esculentus*, onion – *Allium fistulosum*, mung bean – *Vigna radiara*, sesame – *Sesamum indicum*) are normally cultivated on raised beds of around 20 cm height above the field surface, with the soil dug by hoe to 20-30 cm depth for making raised beds and furrows. Prior to sowing for upland crops, farmers clear any remaining crop residue and post-season weeds.

1.6 Objectives of the study

As described above, long-term intensive rice farming has the potential to damage soil health, leading to poor productivity and reduced income. Avoiding the negative effects of the present intensive rice monoculture systems and improving those factors that lead to a reduction in rice yield is fundamental to the food security goal and to enhance farmers' income. However, at present a comparative assessment and scientific evidence of systems on inclusion of non-rice crops in rice-based cropping systems is meager. No information is available on the long term effects of repeated crop rotation applications on rice production in the Mekong Delta region. Therefore, this study was carried out in order to conserve the natural land resources and support sustainable agricultural production in this area. We explored the potential of rotating rice with upland crops, hence alternating soil anaerobic with aerobic conditions, to maintain productivity of paddy soil in the Mekong Delta. The hypothesis was that the soil physical and chemical properties, and rice yield from cropping systems of rice rotated with upland crop such as maize and mung bean systems are different and more beneficial than from an intensive rice monoculture system thus maintaining productivity and farmer’s income without degrading the soil resource. Whether upland crop cultivation with deep tillage performs better than the traditional practices associated with rice monocultures in terms of improved soil structural properties, root growth, nutrition availability stocks and rice yield of the region is still unknown. Therefore, the overall objective of this dissertation was to evaluate the long-term impact of rice-upland crop rotations on soil physical and chemical properties of paddy rice fields as compared with intensive rice monocultures. More specifically, this study will provide insights on how soil quality changes under different cropping systems and thus contribute to sustainable rice production in the Vietnamese Mekong Delta. As our hypothesis is that the new cropping systems will improve soil quality, they are termed soil-improving cropping systems in this dissertation.

To address the above main objective, the following specific objectives of the research are:

(i) to determine the effect of rotations of rice with upland crop on physical and soil chemical soil quality as compared to intensive rice monoculture in the late wet season, i.e. in the rice growing season of all rotations;

(ii) to study the influence of crop rotation versus continuous rice cultivation on the physical and chemical properties of cultivated soil in the dry season, i.e. in the upland crop plots of the rice-upland crops rotation systems, and in the rice plots of the rice monoculture system.

(iii) to assess the impact of upland crop rotations with rice on rice yield and the yield trends;
(iv) to determine the relationship between the physical and chemical soil properties and the rice yield;
(v) to evaluate if soil compaction under rice monoculture system leads to decreased nutrient availability stocks and hence rice yield;
(vi) to evaluate the long-term impacts of rice-upland crop rotations on economic productivity and feasibility;
(vii) to assess the seasonal and inter-seasonal variation of selected hydro-physical properties of a paddy clay soil under difference rotation-based cropping systems;
(viii) to evaluate the effects of different cropping systems on the physical and chemical quality of alluvial heavy clay soils in uncontrolled farmers' fields;
(ix) to recommend prospective cropping systems for paddy rice areas inclined to physical soil degradation and to suggest policy implications related to rice-upland crop rotation systems.

Results of this research would help farmers, agricultural extension agents, policy makers, local authorities and consultants to make appropriate land management decisions for future sustainable cultivation in paddy soils.

1.7 Outline of the dissertation

This dissertation is organized in nine chapters (Fig. 1.6). **Chapter one** introduces the research problems, characteristics of study area, major objectives and the outline of the dissertation. **In chapter two**, we examined whether crop rotations of paddy rice with upland crops as an alternative agricultural management practice for continuous rice cultivation, affected the soil physical properties in the dry season. **In chapter three**, the same was done for the chemical properties. We assessed how crop rotation with upland crops affected the soil chemical properties compared to continuous paddy rice cultivation systems. **In chapter four**, we examined ten years impact of crop rotation on soil physical, chemical properties, and rice yield components and yield in the late wet season after rice cultivation for all different treatments. Besides, farmer's income was also evaluated and how this might affect the economic feasibility of the newly introduced systems. **Chapter five** identifies if limited root penetration under intensive rice monoculture system causes shortage of one or multiple nutrients and likely explains the lower plant performance as compared to rice-upland systems. **Chapter six** presents the impact of different cropping systems on soil compaction and how these properties change with time within crop season and inter-crop season.

Chapter seven presents physical and chemical properties that were assessed to quantify changes due to medium-term application of different cropping system, but on farmer's fields rather than on the experimental plots. **Chapter eight** gives an overview of the socio-economic status and how farm characteristics and crop rotations affect crop yield and income of the households involved in the study area after medium-term changing from rice monoculture system to other cropping systems. **Chapter nine** presents the general discussion of the results reported from chapter two to chapter eight, conclusions, and recommendations for future research and development attention.

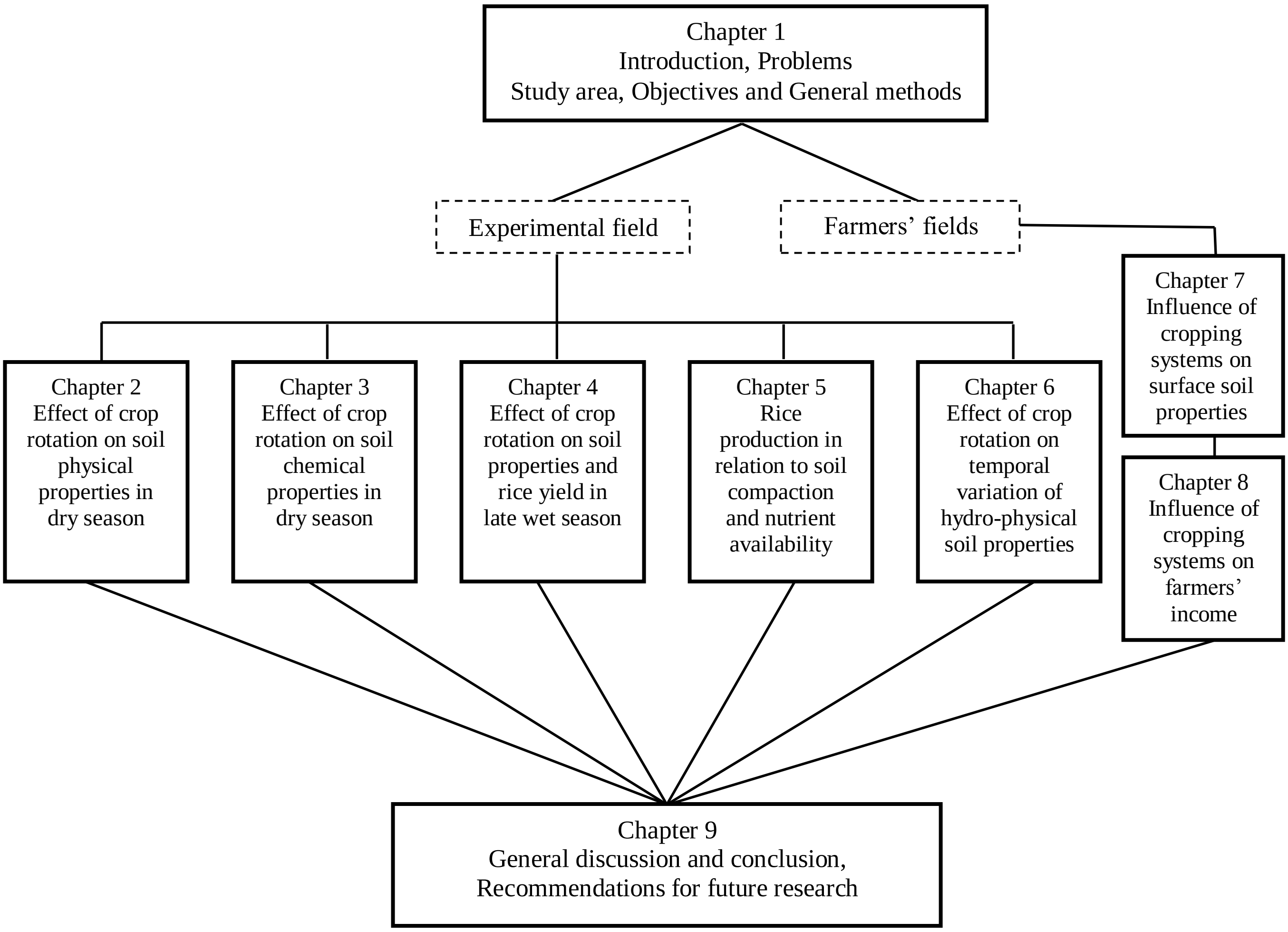


Figure 1. 6 Schematic overview of the dissertation

Chapter 2

Inclusion of upland crops in rice-based rotations affects physical properties of clay soil in dry season[#]

This chapter is based on:

Linh, T.B., Khoa, L.V., Van Elsacker, S., Cornelis, W., 2016. Effect of cropping system on physical properties of clay soil under intensive rice cultivation. Land Degradation & Development 27, 973-982.

2.1 Introduction

The physical quality of agricultural soil refers primarily to the soil's strength and storage characteristics in the crop root zone (Topp et al., 1997). Soil with good physical quality has the ability to store and transmit water, air, nutrients and agrochemicals in ways which promote both maximum crop performance and minimum environmental degradation (Reynolds et al., 2007). Many cropping factors are known to influence soil physical properties. These include tillage (Singh et al., 2014), crop type (Scott et al., 1994), cultivation farming practices (Ozgoz et al., 2013), and soil preparation depending on the kind of crop, like puddling in case of rice farming systems. Effects of cropping and soil management systems on soil physical properties are often related to changes in soil organic matter (Haynes, 2000), soil quality (García Orenes et al., 2009; Barbera et al., 2012; Tesfahunegn, 2013) and provide essential information for assessing sustainability and environmental impact (Ishaq and Lal, 2002; Schneider et al., 2012).

Tillage is used for planting, weeding and to loosen surface and subsurface soil hence alleviating soil compaction. However, continuous intensive monocultures of rice can lead to increased subsoil compaction and reduced soil quality. Indeed, tillage and puddling under wet conditions with machinery is the most common soil preparation technique used to support lowland rice production. The presence of a compacted layer in paddy field helps to reduce water losses and limits plant nutrient leaching through percolation (Reddy and Hukkeri, 1980). However, it is also an obstacle for root penetration if the compacted layers are located at a shallower than the normal rooting depth and hence affect crop growth and yield (Wickramasinghe, 2011). Furthermore, in a rice monoculture system with anaerobic conditions throughout most part of the year, rice crop residue might show problems for season by season decomposition. This might lead to reduced soil organic matter quality by accumulation of phenolic compounds resulting in reduced nutrient availability (Olk et al., 2007; Srinivasarao et al., 2014).

Inclusion of upland crop is desirable to minimize the risks of subsoil compaction. Indeed, selecting rotations which include crops with a strong tap root able to penetrate and break down compacted soil can contribute to alleviating soil compaction and its effects (Hamza and Anderson, 2005; Schjønning et al., 2015). Moreover, excessive and unnecessary tillage and puddling operations are limited in upland crop season(s). Rotation of upland crops and rice with its flooded soils brings a transition in soil aeration status from anaerobic to aerobic and back to anaerobic. The frequent cycling between anaerobic and aerobic condition results in a greater rate of soil organic carbon decomposition (Xu et al., 2007; Motschenbacher et al., 2011). Accordingly, physical properties of long-term flooded paddy soil such as soil structure and porosity can be changed by the rice-upland crop rotation practice (Zhou et al., 2014).

A pilot survey conducted in the Mekong Delta, showed that the plow layer became closer to the soil surface starting at 15-25 cm depth and extending to 20-50 cm. This is mainly due to repeated shallow tillage puddling activity three times per year with machinery trafficking for land preparation under wet conditions for rice monoculture for more than 30 years. The rice yield cultivated on alluvial soils in monocultures with three harvests per year is declining, even though farmers add yearly more fertilizer (Khoa, 2002). In order to develop sustainable rice crop production systems, new cropping systems with different crop rotations within one year were introduced on paddy clayey soil in the Mekong Delta, Vietnam. Based upon the market demands, the technical level of farmers and especially the agricultural development strategy of the local government, mung bean (*Vigna radiata*), which is a leguminous crop, and maize (*Zea mays* L.), a non-leguminous crop, were chosen for rotating with rice (*Oryza sativa*). The rotations comprise a rotation with flooding crops (rice) only, which is now the common practice, and new rotations with rice and upland crops (maize and mung bean). Hence, the new rotations alternate soils anaerobic with aerobic conditions.

Long-term experiments were therefore conducted under different cropping systems on clay soils with the objective of evaluating their impact on selected physical soil quality indicators and to understand to what extent creating temporary beds for upland crops (maize and mung bean) can correct for potential loss in soil quality resulting from rice cultivation. We hypothesize that rotating rice with maize and mung bean grown on temporary beds improves the deteriorated physical quality of soil, and increase rice yield in the subsequent season in comparison with the rice monoculture system.

2.2 Materials and methods

2.2.1 Site description and treatments

The field experiment was performed as described in Chapter 1 (section 1.5).

2.2.2 Soil sampling and field measurement

A specific focus of our experiment was the vertical variability of some soil properties under the different crop rotations. For this reason, samples were taken once for 10 cm depth increments down the profile. In this season (spring-summer season), different crops (rice, mung bean, maize) were cultivated in different treatments. Rice was planted on flat field whereas maize and mung bean were cultivated on raised beds. For maize and mung bean plots, the soil samples were taken in the beds where the plants were cultivated. For rice plots, the soil samples were taken on the flat. All soil samples were taken after 25 cropping seasons at the same time at the end of the spring-summer cropping season (dry season) when the soil was almost saturated, which corresponds under our conditions to field capacity.

Undisturbed soil samples were taken with 100 cm^3 rings at three depths (0-10, 10-20 and 20-30 cm) following the procedure described by Dirksen (1999). The core samples were used for the determination of soil water retention and bulk density. Disturbed soil samples at three depths (0-10, 10-20 and 20-30 cm) were taken for soil organic carbon, soil texture, soil particle density and soil aggregate stability analysis; every sample was a randomized composition from ten locations within one plot using a sampling tube type auger.

Soil penetration resistance was measured with a handheld electronic penetrometer (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) directly in the field. This instrument was used to measure resistance of up to 10 MPa pressure to a depth of 80 cm in one centimeter intervals. These measurements were repeated three times in each of the four replicate plots per treatment and values were averaged per plot. Concurrently with soil strength measurements, soil moisture content was determined in 10 cm intervals until 80 cm depth.

2.2.3 Determination of soil physical properties

The Robinson pipette method (Gee and Bauder, 1986) was used to analyze soil particle size distribution. The sand (0.05-2 mm), silt (0.002-0.05 mm) and clay (<0.002 mm) fraction of the soil sample was determined and the USDA/Soil Taxonomy texture triangle was used to classify soil texture. Bulk density was calculated as oven dry soil weight (105 °C) of undisturbed soil samples per bulk volume unit using the core method (Grossman and Reinsch, 2002). Particle density was determined using the pycnometer method (Blake and Hartge, 1986) with all air being removed by a vacuum pump. Total porosity was then calculated from bulk density and particle density (Vomocil, 1965). For soil water retention characteristics, the sand-box apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) was used for matric potentials between 0 and -10 kPa, whereas pressure chambers (Soilmoisture Equipment, Santa Barbara CA, USA) were used for tensions from -33 to -1,500 kPa on core sub-samples, following the procedure described in Cornelis et al. (2005). The van Genuchten equation (1980), an effective and commonly used parametric model for relating water content to matric potential, was fitted to the measured water retention data for calculating the S-index:

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{1}{1+(\alpha|h|)^n}\right)^m \tag{1}$$

where θ is water content (kg kg^{-1}), h is matric potential head (cm), θ_r is residual water content (kg kg^{-1}), θ_s is water content at saturation (kg kg^{-1}), and α, n, m are fitting parameters with m set at 1-1/n, and α in cm^{-1}.

Dexter (2004a, 2004b, 2004c) defined a quantity S as the slope of the water retention curve at its inflection point. He noted that values of S appeared to have the same physical meaning in soils of all textures. This index has been related to many important soil properties or conditions including compaction, penetration resistance, plant-available soil water and soil structural stability (Dexter and Czyz, 2007). We therefore used the S index to better understand the effect of different crop rotation systems on soil structural quality and to compare it with soil compaction data.

The S-index was calculated using Equation (2)

$$S = n(\theta_s - \theta_r)\left(\frac{2n-1}{n-1}\right)^{\frac{1}{n}-2} \tag{2}$$

where n, θ_s, θ_r are the van Genuchten parameters obtained by curve-fitting Equation (1) to the measured retention data. θ_s and θ_r are the saturated and residual gravimetric water contents, respectively (kg kg^{-1}). Note that θ_r was set to zero as suggested by Dexter (2004b). These parameters were estimated and calculated with the RETC retention curve program (RETC, 2008).

Plant available water capacity (PAWC) was calculated as Equation 3

$$PAWC = \theta_{fc} - \theta_{pwp} \tag{3}$$

where θ_{fc} and θ_{pwp} are water content at field capacity and at permanent wilting point (m^3 m^{-3}). A matric potential of -10 kPa was taken as corresponding to field capacity (Romano and Santini, 2002), according to field observations in the study area reported in Khoa (2002). Wilting point was considered at a matric potential of -1,500 kPa (Reynolds et al., 2007).

The stability of the aggregates was determined on air-dried soil disturbed samples using the dry and wet sieving method of de Leenheer and de Boodt (1959) in the laboratory. The difference in the weighted quantities of the aggregate sizes between dry and wet sieving is an index for aggregate instability (Equation 4 and 5):

$$IS = MWDd - MWDw \tag{4}$$

with

$$\mathrm{MWD} = \frac{\sum mi * di}{\sum mi} \tag{5}$$

where *IS* is the instability index, *MWD* is mean weighted diameter of the dry (d) and wet (w) aggregate fractions, *mi* is mass of the aggregate fraction i (g), and *di* is mean diameter of the aggregate fraction i (mm).

The stability index (*SI*) was calculated as the inverse of the difference in mean weighted diameter after dry and wet sieving (Equation 6):

$$\mathrm{SI} = \frac{1}{IS} \tag{6}$$

2.2.4 Statistical analyses

Analysis of variance (ANOVA) was conducted on all investigated soil properties with crop rotation and depth layer as fixed factors. Differences among individual treatments were determined using Duncan's multiple range test ($P < 0.05$). All analyses were carried out with SPSS (version 20.0, IBM, Armonk, NY, USA).

2.3 Results

2.3.1 Soil texture

The soil textural class of the whole experimental area was clay, with a mean of 2% sand, 32% silt and 66% clay (Table 2.1). There were no significant differences in sand content between treatments for three depths 0-10, 10-20 and 20-30 cm and between depths within the treatment. Clay content was not significantly different between all the treatments at 0-10 cm depth. However, at depth 10-20 and 20-30 cm, clay content of R-R-R was significantly higher (2-4% higher) than that of cropping systems with rice and upland crops except for R-Mb-R. In the those systems there was no significant difference between depths of 0-10 cm and deeper layers except for R-Mb-M, whereas R-R-R treatment manifested a significant increase in clay content with depth with the highest value (69.8%) at 20-30 cm depth. In contrast to clay content, the silt content was significantly lower in R-R-R compared to R-M-R, R-Mb-R and R-Mb-M treatments.

Table 2. 1 Particle size distribution for the different crop rotation treatments at three different depths[1]

Treatment	Depth (cm)	Sand 50–2000µm	Sand* 50–2000µm	Silt 2–50µm	Silt* 2–50µm	Clay <2µm	Clay* <2µm
				(g kg^{-1})			
R-R-R	0-10	22.8±3.1	20.6	324.2±16.2$_{a}$	302.7	653.0±12.1$_{b}$	676.7
	10-20	19.8±3.6		301.0±16.7$^{B}_{ab}$		679.4±18.6$^{A}_{a}$	
	20-30	19.4±4.5		282.9±17.9$^{B}_{b}$		697.7±21.4$^{A}_{a}$	
R-M-R	0-10	25.0±4.1	24.5	324.1±8.6$_{ab}$	323.1	650.9±10.3$_{ab}$	652.4
	10-20	24.4±2.7		330.0±15.5$^{A}_{a}$		645.6±16.6$^{B}_{b}$	
	20-30	24.0±2.3		315.2±14.2$^{A}_{b}$		660.8±15.8$^{B}_{a}$	
R-Mb-R	0-10	23.2±3.5	23.3	336.6±25.9	313.2	640.1±27.2	663.5
	10-20	23.9±3.7		309.6±15.7^{AB}		666.5±16.7^{AB}	
	20-30	22.9±3.1		293.4±22.6^{AB}		683.8±21.5^{AB}	
R-Mb-M	0-10	24.2±2.0	23.4	329.2±11.7$_{a}$	321.1	646.6±11.2$_{b}$	655.5
	10-20	23.3±0.8		316.5±5.7$^{AB}_{b}$		660.2±6.4$^{AB}_{a}$	
	20-30	22.7±3.3		317.7±5.6$^{A}_{b}$		659.6±4.4$^{B}_{a}$	

[1] *R-R-R, rice-rice-rice; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation; *, soil parameters of 0-30 cm depth. Different letters in each column mean statistically significant differences at $P < 0.05$ using DMRT; A, B, C are the significant differences between the treatments of each depth; a, b, c are the significant differences between the depths within the treatment. Numbers follow ± symbol represent the standard deviations.*

Table 2. 2 Influence of crop rotations on selected soil physical quality indicators and parameters[1].

Treatment	Depth (cm)	BD (Mg m^{-3})	BD* (Mg m^{-3})	PD (Mg m^{-3})	SP (%)	SP* (%)	PAWC (m^3 m^{-3})	PAWC* (m^3 m^{-3})	SI	SI*	S-index	S-index*
R-R-R	0-10	$0.91\pm0.02^{B}{}_{c}$	1.12A	$2.39\pm0.03_{b}$	$62.09\pm1.41_{a}$	54.67B	$0.251\pm0.01^{AB}{}_{a}$	0.224B	$1.44\pm0.23^{B}{}_{a}$	1.21C	$0.07\pm0.001_{a}$	0.05B
	10-20	$1.13\pm0.06^{A}{}_{b}$		$2.47\pm0.04_{a}$	$54.24\pm2.02^{C}{}_{b}$		$0.237\pm0.01_{a}$		$1.31\pm0.16^{B}{}_{a}$		$0.05\pm0.01^{B}{}_{b}$	
	20-30	$1.32\pm0.05^{A}{}_{a}$		$2.53\pm0.02^{A}{}_{a}$	$47.67\pm2.10^{B}{}_{c}$		$0.185\pm0.03^{C}{}_{b}$		$0.88\pm0.17^{C}{}_{b}$		$0.03\pm0.01^{B}{}_{c}$	
R-M-R	0-10	0.96 ± 0.04^{AB}	0.95B	2.45 ± 0.03	60.74 ± 2.17	61.41A	0.252 ± 0.06^{AB}	0.235AB	1.81 ± 0.20^{AB}	1.86B	0.07 ± 0.02	0.06A
	10-20	0.94 ± 0.06^{BC}		2.48 ± 0.01	62.08 ± 2.28^{AB}		0.224 ± 0.03		1.85 ± 0.12^{A}		0.06 ± 0.001^{A}	
	20-30	0.96 ± 0.06^{B}		2.49 ± 0.05^{AB}	61.40 ± 2.77^{A}		0.231 ± 0.04^{B}		1.93 ± 0.31^{AB}		0.06 ± 0.01^{A}	
R-Mb-R	0-10	$0.95\pm0.06^{AB}{}_{ab}$	0.96B	2.46 ± 0.05	$61.26\pm2.63_{ab}$	61.30A	0.234 ± 0.02^{B}	0.245AB	2.16 ± 0.25^{A}	2.11A	0.06 ± 0.01	0.07A
	10-20	$0.92\pm0.04^{C}{}_{b}$		2.48 ± 0.05	$62.86\pm1.54^{A}{}_{a}$		0.230 ± 0.03		2.14 ± 0.35^{A}		0.06 ± 0.001^{A}	
	20-30	$0.99\pm0.03^{B}{}_{a}$		2.47 ± 0.04^{B}	$59.77\pm1.54^{A}{}_{b}$		0.272 ± 0.03^{A}		2.04 ± 0.27^{A}		0.07 ± 0.02^{A}	
R-Mb-M	0-10	$1.11\pm0.03^{A}{}_{ab}$	1.01B	2.47 ± 0.04	59.05 ± 1.55	58.79A	$0.288\pm0.02^{A}{}_{a}$	0.272A	1.91 ± 0.31^{A}	1.78B	0.07 ± 0.01	0.07A
	10-20	$1.00\pm0.01^{B}{}_{b}$		2.46 ± 0.06	59.32 ± 1.46^{B}		$0.256\pm0.03_{b}$		1.85 ± 0.16^{A}		0.06 ± 0.01^{A}	
	20-30	$1.03\pm0.01^{B}{}_{a}$		2.45 ± 0.02^{B}	58.01 ± 0.33^{A}		$0.271\pm0.02^{A}{}_{ab}$		1.60 ± 0.25^{B}		0.07 ± 0.001^{A}	

*[1] R-R-R, rice-rice-rice; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation; BD, bulk density; PD, particle density; SP, soil porosity; PAWC, plant available water capacity; SI, stability index; S-index, Dexter's physical soil quality index; *, soil parameters of 0-30 cm depth.*
Different letters in each column mean statistically significant differences at $P < 0.05$ using DMRT; A, B, C are the significant differences between the treatments of each depth; a, b, c are the significant differences between the depths within the treatment. Numbers follow ± symbol represent the standard deviations.

2.3.2 Bulk density (BD) and soil porosity (SP)

Between the treatments at depth of 0-10 cm, BD was significantly higher for the cropping systems of rice with two upland crops (R-Mb-M) as compared to the rice mono culture (R-R-R) and was not significantly different compared to R-M-R and R-Mb-R. However, at depth of 10-20 and 20-30 cm, BD was significantly higher for R-R-R than all the other rotations. Across depths, BD in R-R-R was significantly higher (25-46%) at 10-20 and 20-30 cm compared to 0-10 cm (Table 2.2), while no differences in BD with depth were perceived in rice and upland crop rotation treatments.

The changes in SP (Table 2.2) values were not significantly different in R-M-R, R-Mb-R and R-Mb-M when compared to R-R-R in the topsoil (0-10 cm). However, opposite to the top soil, SP of R-M-R, R-Mb-R and R-Mb-M were significantly higher compared to R-R-R at depth of 10-20 and 20-30 cm. The SP at 0-10 cm depth of R-R-R was significantly higher than deeper depths, while the SP at 0-10 cm depth of R-M-R, R-Mb-R and R-Mb-M was not significantly different compared to depths 10-20 and 20-30 cm. Considering the top 30 cm, BD and SP were significantly affected by the cropping system with the highest value of BD (1.12 Mg m^{-3}) and the lowest value of SP (54.67%) in R-R-R (Table 2.2).

2.3.3 Soil strength

The largest difference in soil strength between all treatments was observed at 20-50 cm depth (Figure 2.1). At these depths, measured soil strength was substantially higher for R-R-R (~3.5 MPa) than the other cropping systems. This is probably due to the plow layer (hard pan) and the lower soil water content (as it is well known that drier soil shows greater strength). The soil strength did not increase under a depth of 50 cm.

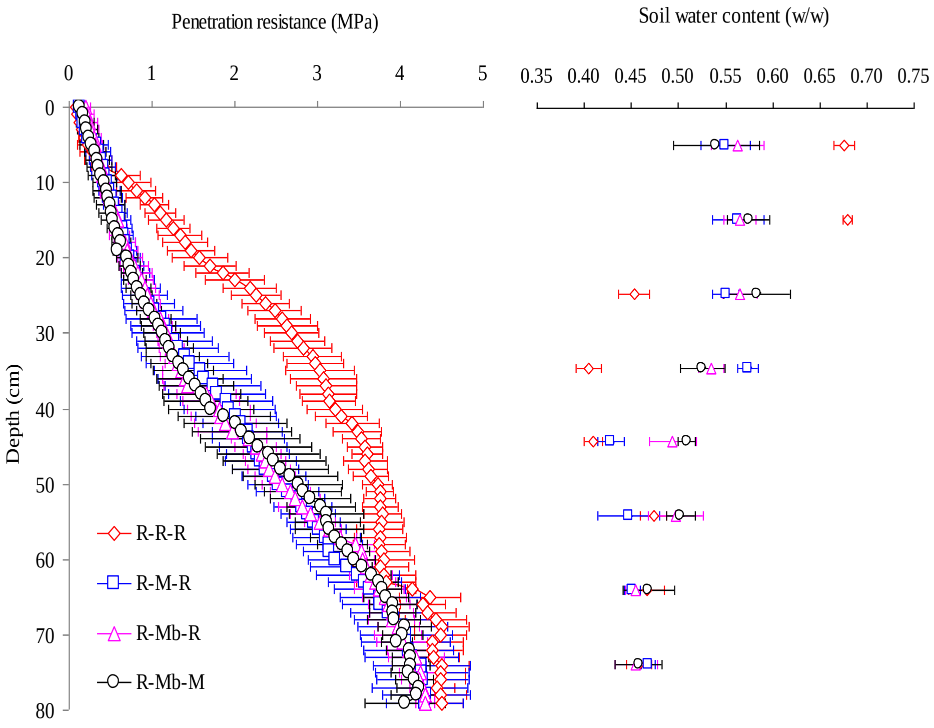


Figure 2. 1 Soil strength and corresponding soil water content averaged for four replicates in rice-rice-rice (R-R-R), rice-maize-rice rotation (R-M-R), rice-mung bean-rice rotation (R-Mb-R), rice-mung bean-maize rotation (R-Mb-M). Bars represent standard deviations for each cropping system.

2.3.4 Soil aggregate stability

In this study, the stability index (SI; Table 2.2) was used as a measure of aggregate stability. The use of upland crops in the cropping systems showed an improvement in SI compared to rice monoculture. Indeed, all cropping systems of rice with upland crops had a significant higher SI than the intensive rice monoculture system, at all depths, except R-M-R at depth 0-10 cm. This higher of SI (26-50%, 41-63% and 82-131% at depth of 0-10, 10-20 and 20-30 cm, respectively) in comparison with R-R-R was visible in R-M-R, R-Mb-R and R-Mb-M.

In R-R-R, SI at depth of 0-10 and 10-20 cm was significantly higher than at 20-30 cm depth. In cropping systems of rice with upland crops the difference in SI between the depths was less explicit, as the differences in SI were not significant at 0-10 cm compared to 10-20 and 20-30 cm depth. The cropping system also significantly affected SI at overall depth of 0-30 cm, with the highest value in R-Mb-R (2.11), followed by R-M-R (1.86) and R-Mb-M (1.78), while R-R-R (1.21) showed the lowest value (0-30 cm) (Table 2.2).

2.3.5 Dexter's physical soil quality index (S-index)

S index generally improved when introducing upland crops, with rice and upland crop rotation systems showing the highest S value across 0-30 cm depth and the intensive rice monoculture system the lowest (Table 2.2). Also, S index of R-R-R was significantly lower (15-18% and 43-51% lower for depth of 10-20 and 20-30 cm, respectively) than all other treatments. However, the S index of R-R-R was not significantly different from that of the other treatments at 0-10 cm depth.

A significant decrease of the S index with depth was observed in R-R-R (28-52% decrease for 10-20 and 20-30 cm depths). All other treatments showed no significant difference between the depths (Table 2.2).

2.3.6 Plant available water capacity (PAWC)

Plant available water capacity was not significantly different between cropping systems including rotations with upland crops and rice monoculture at 0-10 and 10-20 cm depths (Table 2.2). At depth of 20-30 cm, cropping systems with rice and upland crops showed significantly higher PAWC (25-47% higher) than R-R-R. In the treatments with upland crops, no significant differences in PAWC between the depths of 0-10, 10-20 cm and 20-30 cm were observed, in contrast with R-R-R were PAWC was significantly lower at 20-30 cm depth as compared to the top 20 cm.

Comparison of overall PAWC in the top 30 cm data showed significant differences in R-Mb-M and R-R-R. However, we found no significant differences in PAWC among the cropping systems with alteration of paddy rice and one upland crop (R-M-R, R-Mb-R) or two upland crops (R-Mb-M). PAWC was not significantly different between treatments with two rice crops and one upland crop (R-M-R, R-Mb-R) and intensive rice monoculture (R-R-R) (Table 2.2).

2.4 Discussion

Preparing temporary beds in which soil was taken from below did not result in significantly different sand content in the top 30 cm. However, clay content of R-R-R was significantly higher at depth of 20-30 cm than 0-10 and 10-20 cm depths. This can be due to repeated shallow tillage activity for rice mono-culture for more than 30 years prior to the experiment in which with time fine-textured soil material moves down with rain or irrigation water and gradually fill up the soil interstices.

Silt and clay content of treatments with upland crop rotations was not significantly different among depth due to eight years soil mixing when preparing temporary beds. Overall, the clay content of the soil in the study location was high (>60%), which makes them very susceptible for soil compaction and increased soil resistance in the subsoil (Inge and Jerzy, 2000).

The increment in SOC in cropping systems with rice and upland crops (see Chapter 3) might have contributed to the increase in soil porosity (Bhattacharyya et al., 2006), soil aggregate stability (Pagliai et al., 2004), S-index, PAWC (McGarry et al., 2000) and reduced susceptibility to soil compaction in particularly subsoil horizons (Table 2.2). The findings by Tesfay et al. (2012) on agriculture Vertisols in Ethiopia substantiated the importance of SOC as sensitive soil quality indicator. Zhao et al. (2013) also report SOC as good soil quality indicator for silt loam soil in China. The higher BD and lower SP in the subsoil of R-R-R were due to the machine tillage carried out every rice crop season before sowing within the top 10 cm. Though such compacted layer is typically aimed at in paddy rice cultivation to minimize drainage losses, such shallow compacted layer may aggravate cropland degradation and lead to lower rice crop yield in the long term. Rotations with upland crops provide a higher rate of soil mixing, and thus BD and SP did not differ much with depth. This also illustrated the advantage of the temporary bed planting system in rotations with at least one upland crop in breaking down the compacted layer during bed preparation and the formation of more stable aggregates (Table 2.2).

The R-Mb-M treatment had a slightly higher BD (5-10% increases) than the other rotations with upland crops. With two upland crops, less residue results in less SOC (Chapter 3), which might increase BD as suggested by the high correlation between SOC and BD found in our experiments (r=-0.84). However, BD in this treatment was still within the optimum range (0.9-1.2 Mg m^{-3}) for fine-textured soils (Reynolds et al., 2007). Similar differences in BD due to differences in SOC have been observed for loamy soil by Reynolds et al. (2007) and for clay soil by Cotching et al. (2002). Although Reynolds et al. (2003, 2007) and Drewry (2006) suggest the 0.9 to 1.2 Mg m^{-3} range as optimal for crop production on fine-textured soils, the upper limit in fine-textured soil is 1.25–1.30 Mg m^{-3} (McQueen and Shepherd, 2002), whereas root elongation becomes severely restricted in fine textured soil at BD values of 1.4–1.6 Mg m^{-3} (Jones et al., 2003). Ni (1995) reported that for clay soil, a BD value higher than 1.35 Mg m^{-3} entails susceptibility to compaction of the paddy subsoil layer which leads to limited root elongation and reduced rice crop yield. In our experiments, BD values at 20-30 cm of R-R-R treatment are approaching this limit. Hence, rice crop growth in this treatment is likely to be impaired by excessive soil BD.

Soil strength was significantly higher under R-R-R which can limit plant growth by restricting root elongation (Cotching and Belbin, 2007). The difference in soil strength between the cropping systems with upland crops was not significant. These findings are supported by the observed bulk density and total porosity. Overall, the soil strength values were very high which might partly be explained by the high clay content but mainly by soil compaction. In the study of Cotching et al. (2002) on Vertisols with high clay content the penetration resistance increased to a mean value of 3.2 MPa at a depth of 60 cm. In our study location in the Mekong Delta, clay content was even higher compared with that of the study of Cotching et al. (2002), resulting in an even higher penetration resistance (between 3 and 4 MPa at a depth of 60 cm). A penetration resistance above 2 MPa would slow down root penetration drastically (Lowery and Morrison, 2002). Changing rice monocultures to crop rotation systems with one or two upland crops would facilitate roots to penetrate more readily. In R-R-R, a substantial increase in the degree of compaction can be noticed from a depth of already 10 cm onwards, whereas in treatments with upland crops soil strength increased more gradually. The absence of frequent tillage and good aeration conditions in crop rotation systems with upland crops could enhance the soil porosity (Table 2.2) which leads to lower soil strength thereby reducing soil compaction. The compaction observed in the subsoil horizon below the cultivated layer in all treatments might be due to machinery used when preparing the land for rice year by year. Sharma and De Datta (1985a) have shown that long–term puddling forms a hardpan in the subsoil below the puddled layer of paddy fields.

SI value in R-R-R treatment at 20-30 cm depth was lowest (0.88) and more than 30% lower compared to the upper layers. This may imply the higher sensitivity at 20-30 cm depth of R-R-R to structural degradation induced from mechanical tillage in the top 10 cm. The introduction of cropping systems with upland crops showed an improvement in SI and hence PWAC compared to rice monoculture at all depths, but especially in the 20-30 cm depth. A significant higher amount of SOC, a lower soil BD and the absence of repeated mechanical tillage in cropping systems with upland crops compared to rice monoculture might explain its increase in SI and PAWC. We found a correlation r between SI and SOC of 0.52 and the correlation was significant at the 0.01 level, leading to the conclusion that soils with high SOC are high in stable soil aggregate stability and low in soil compaction (Kocyigit and Demirci, 2012). Such positive correlation was also reported by Elliot (1986) and Smith and Elliot (1990). The results are similar to those of Hobbs et al. (2008) who found aggregate stability to increase under reduced tillage with organic residue retention. According to Tisdall and Oades (1982) and Six et al. (2004), the most important factors affecting aggregation and stabilization of soil particles are organic matter and binding agents produced by microorganisms, root activities, soil fauna, inorganic binding agents and environmental conditions. Compaction forces soil particles closer together and increases the BD of the soil, resulting in larger pores being eliminated and loss of soil aggregation (Cotching and Kidd, 2010). Even though there existed a relation between SOC and SI, it was probably not causal because SOC seemingly is not a crucial binding agent in soil with clay content > 65%. Elevated SOC content by deeper soil mixing and improved SI by inclusion of dry soil periods, both under rice-upland crop rotations, could well be independent from one another. Overall the rather high SI values in our soils suggest good structural condition. This may be due to high clay content in soil. According to Kemper and Koch (1966) aggregates have been found to increase with increasing clay content. Further, Le Bissonnais (1996) and Amezketa (1999) reported that clay is one of the aggregating factors in soil acting as a cementing agent. Additionally, aggregate stability is also related to the organic carbon content; the higher soil organic matter, the higher is the stability of the soil aggregates (Cerdà, 2000; Kocyigit and Demirci, 2012).

For fine-textured soil, Cockroft and Olssen (1997) recommended that PAWC should be higher than 0.20 $m^3 m^{-3}$ to enable maximum root growth and to minimize susceptibility to ‘droughtiness’. The PAWC value at 20-30 cm of R-R-R was only 0.18 $m^3 m^{-3}$ and fell below the lower critical limit of 0.20 $m^3 m^{-3}$ which corresponds to the boundary between the risk and degraded categories for maintaining soil quality. These values are relevant for upland crop cultivation, particularly in the dry season, since lower PAWC values means that more irrigation water is needed to meet the crops water requirements, or that even drought stress might ensue when the land is not optimally irrigated.

The higher SI and PAWC, lower BD and soil penetration resistance as reported earlier might have also increased the S index in the rotations with upland crops. The S index, which is related to the structural porosity of soil, was proposed by Dexter (2004a) for temperate soils, but has also been used and validated for tropical soils by Tormena et al. (2008). This index, though sometimes contested, has been successfully used in several studies (e.g., Reynolds et al., 2009; Zhangliu et al., 2009; Silva et al., 2011). Our results showed that there was a linear S index increase with porosity and a linear decrease with the bulk density (r=-0.60) and this explains the lower S index values for R-R-R at the compacted layer (20-30 cm depth). Similar to these findings, Reynolds et al. (2009) found a high correlation between these two soil quality indicators for all types of soil texture, except for some sandy soils. The lowest S index at 20-30 cm depth for R-R-R treatment is supported by the observed bulk density, soil porosity, soil strength, soil aggregate stability and plant available water, and reflected the compacted layer at 20-30 cm depth of R-R-R treatment.

Cropping system effects were evident for several measured soil properties when considering data aggregated over the complete 0-30 cm layer. In rice and upland crop rotation systems, a better perceived soil physical quality was suggested by lower BD and soil strength, and greater SOC (Chapter 3), SI and S index. This is due to reduced soil compaction and increased SOC as a result of long term rotation rice with upland crops. In contrast, seasonal tillage probably resulted in greater compaction and BD at 20-30 cm in the R-R-R system. Although PAWC was not significantly different between rotations with two rice crops and one upland crop (R-M-R, R-Mb-R) and intensive rice monoculture (R-R-R) over 0-30 cm, numerical differences among R-M-R, R-Mb-R and R-R-R systems reflected the positive influence of systems with crop rotations on PAWC.

2.5 Conclusions

Experiments after twenty-five cropping seasons (8 years) demonstrate that cropping systems of rice and upland crop rotations with temporary beds could improve soil quality compared to long-term intensive rice mono cultivation. Positive effects were demonstrated at all soil depths, especially at 10-20 and 20-30 cm. These new cropping systems not only result in lower soil compaction within the root-zone but also enhance soil aggregate stability, S index and plant available water capacity. Cropping systems with rotations of rice and upland crops can be a possible solution to avoid further degradation of the paddy soil in the Mekong Delta.

Chapter 3

Inclusion of upland crops in rice-based rotations affects chemical properties of clay soil in dry season#

This chapter is based on:

Linh, T.B., Sleutel, S., Elsacker, S.V., Guong, V.T., Khoa, L.V., Cornelis, W.M., 2015. Inclusion of upland crops in rice-based rotations affects chemical properties of clay soil. Soil Use and Management 31, 313-320.

3.1 Introduction

Continuous rice planting can have a negative impact on soil properties (Cassman et al., 1995; Dobermann and Witt, 2000). With long-term submergence and mineral fertilizer application, paddy soils experience degradation of soil quality, such as breakdown of stable aggregation and deterioration of soil organic matter (SOM), which negatively affects agricultural sustainability (Boparai et al., 1992; Mohanty and Painuli, 2004). Organic matter quantity increases following prolonged submergence of soil, with the latter also changing the chemistry and quality of soil organic matter e.g. $C_{hydrolysable}$, which influences nitrogen mineralization (Sahrawat, 2010). $C_{hydrolysable}$ content is considered a quick reactive indicator of soil productivity and soil health as well as an important supply of energy and nutrients for soil micro-organisms and it releases part of the nutrients for plant usage. It provides short-term organic matter turnover during the year (Strosser, 2010). Moreover, the effects of changes in soil management are observable sooner in $C_{hydrolysable}$ than in total SOC (Lee et al., 2009).

Over the past years, various cropping systems have been proposed and tested to preserve or improve soil quality. One of these systems is the rotation of economically viable crops (Wall, 2006; Fuentes et al., 2009). Crop rotations that include multiple crops often favor buildup of soil organic carbon as well as maintenance of various plant (micro)nutrient contents in comparison with monocultures (Robinson et al., 1996; Moore et al., 2000). Paddy rice - upland crop rotations have been recommended and used to improve soil quality and reduce inputs (Witt et al., 2000).

Rotations with strong tap root crops can alleviate soil compaction (Hamza and Anderson, 2005; Schjønning et al., 2015), resulting in an appropriate development of a deep and extensive root system and thus more root-derived C inputs into the subsoil. This may have impacted crop growth and yield. Several researchers reported that rice yield increases with upland crop inclusion in rice based rotations and this practice promotes sustainable agriculture (Filizadeh et al., 2007; Song et al., 2012; Xuan et al., 2012; Mandal et al., 2014). Moreover, inclusion of upland crops, especially legumes, in crop rotations would help to restore the soil’s natural fertility and crop productivity explaining better crop yields. Rotations with legume crops can increase soil nitrogen availability for the cereal crop through symbiotic N_2-fixation by the legume (Pierce and Rice, 1988) and improved nitrogen use efficiency (Lassaletta et al., 2014; Anglade et al., 2015). In addition, rotation of upland crops and rice with its flooded soils brings a transition in soil aeration status from anaerobic to aerobic and back to anaerobic. The frequent cycling between anaerobic and aerobic condition results in a greater rate of soil organic carbon decomposition (Xu et al., 2007; Motschenbacher et al., 2011).

In the Mekong Delta of Vietnam, where this study was conducted, three rice crops (winter-spring, spring-summer and summer-autumn crops) have been cultivated since 1980. After harvest of one rice crop, the soil is irrigated and the flooded soil tilled and puddled with a machine-driven plow before the next crop is planted. This is process occurs three times per year. The widespread stagnation and occasional decline in rice productivity over recent decades has become a matter of serious concern for intensive rice monoculture in the delta (Khoa, 2002). A decline in soil chemical fertility, among several other factors including soil physical quality (as discussed in Chapter 2), is thought to be responsible.

Field experiments provide the best means of studying the long-term fate of agricultural systems, and are of great help in formulating future strategies for maintaining soil quality (Swarup, 1998; Hati et al., 2006). We therefore evaluated changes in several soil chemical quality parameters (soil pH, electric conductivity, cation exchange capacity, soil organic carbon (SOC) content, a presumed labile SOC pool and total soil acidity) under long-term rotations of rice with upland crops in paddy fields.

The intent of this study was to compare chemical properties in the dry season (spring-summer season) under rice-based crop rotations with the annual inclusion of one or two upland crops. We hypothesized that cropping systems with rotations of rice and maize or mung bean grown on temporary beds would improve soil chemical properties, and increase rice yield in the subsequent season in comparison with the rice monoculture system.

3.2 Materials and methods

3.2.1 Site description, field experiment and soil sampling

Site description and field experiment was previously presented in Chapter 1 section 1.5. Soil sampling was previously presented in Chapter 2 section 2.2.2.

3.2.2 Soil analysis

Disturbed soil samples were used for chemical analysis including soil $pH_{(H2O)}$, CEC, electrical conductivity (EC), total acidity (TA), SOC content and hydrolysable labile carbon ($C_{hydrolysable}$). The pH of air-dried soil samples was measured in a 1:5 soil:deionized water suspension using a glass electrode (OKAION pH/mV/C0 meter, Eutech Instruments, Nijkerk, The Netherlands). The electrical conductivity of the soil (EC) was measured with an EC-meter (Schott Instruments D-55122, Mainz, Germany) on 1:5 soil:water suspensions. CEC was determined according to the method of Gillman (1979). Ba (from $BaCl_2$) was used to remove the adsorbed cations, after which Ba was precipitated as $BaSO_4$, with $MgSO_4$. The amount of Mg ions was used to calculate CEC. Soil Organic Carbon (SOC) was determined by the Walkley and Black (1934) method assuming an oxidation efficiency of 75%. Acid hydrolysis by 6M HCl was used to quantify a relatively labile C pool (Silveira et al., 2008), calculated from the subtraction of 6M HCl hydrolysis resistant C content from the total SOC content. For the analysis of total acidity ($cmol_c$ kg^{-1}), soil was extracted with 1M KCl and titrated by 0.01M NaOH (Begheijn, 1980).

SOC and $C_{hydrolyzable}$ stocks (Mg ha^{-1}) were calculated for each soil depth increment as follows: SOC or $C_{hydrolyzable}$ stocks = SOC or $C_{hydrolyzable}$ concentration (%) x BD x d x 10,000, where *d* is the thickness of the soil layer (m), *BD* is bulk density (Mg m^{-3}). The total rice grain and straw dry matter yield were also collected in the subsequent season when rice was grown in all treatments.

3.2.3 Data analysis

Data analyses were performed as described in Chapter 2.

3.3 Results

The soil pH ranged from 5.15 to 5.55 and was not significantly different between the three depth increments or four cropping systems treatments (Table 3.1). Electrical conductivity (EC) ranged from 404.0 µS cm^{-1} to 738.8 µS cm^{-1} and was not significantly different between cropping systems or depths, with the exception of R-Mb-M at 10-20 cm depth where EC was significantly smaller (404.0 µS cm^{-1}) than in other rotations (Table 3.1). CEC in the 0-10 and 10-20 cm depth layers was significantly ($P < 0.05$) larger under the R-Mb-R and R-Mb-M compared with the R-R-R cropping system. R-M-R did not alter cation exchange capacity (CEC) relative to the other treatments. CEC did not differ significantly with depth within the same cropping system treatment, except for a significantly greater CEC for R-R-R at 20-30 cm relative to the two upper layers (Table 3.1). Total acidity (TA) in the 0-10 and 10-20 cm depth layers was significantly less for cropping systems of rice with mung bean (R-Mb-R and R-Mb-M) than under rice monoculture (R-R-R), while no significant differences between rotations were found at 20-30 cm depth (Table 3.1).

Table 3. 1 Influence of cropping system on soil pH, electric conductivity (EC), cation exchange capacity (CEC) and total acidity (TA) in three depth intervals (means ± standard deviations; n=4)

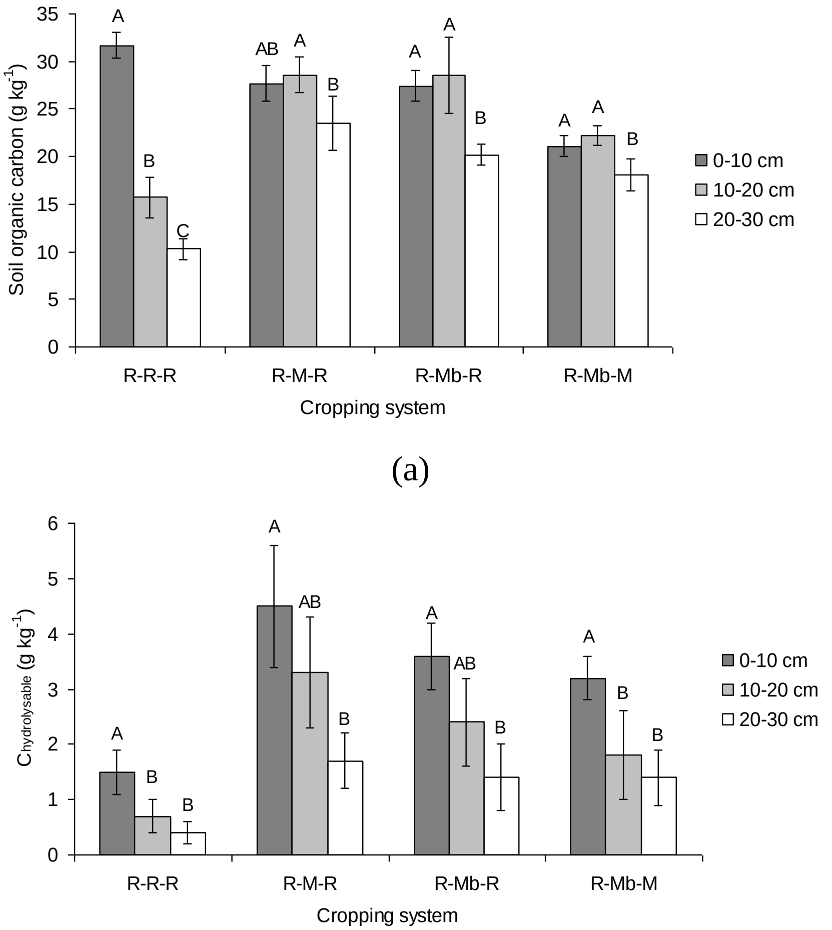
Cropping system[a]	Depth (cm)	pH (-)	EC (µS cm^{-1})	CEC (cmol+ kg^{-1})	TA (cmol kg^{-1})
R-R-R	0-10	5.35 ± 0.42	661.6 ± 81.28	21.21 ± 0.44B b	0.421 ± 0.305A
	10-20	5.27 ± 0.24	623.9 ± 47.93A	21.76 ± 0.81B b	0.418 ± 0.323A
	20-30	5.50 ± 0.32	625.0 ± 60.93	24.02 ± 1.73AB a	0.227 ± 0.390
R-M-R	0-10	5.15 ± 0.19	671.0 ± 140.55	22.90 ± 1.12AB	0.371 ± 0.099AB a
	10-20	5.40 ± 0.15	626.0 ± 49.48A	23.21 ± 1.03AB	0.185 ± 0.102AB b
	20-30	5.23 ± 0.04	711.9 ± 137.13	22.19 ± 1.19B	0.401 ± 0.061 a
R-Mb-R	0-10	5.30 ± 0.13	738.8 ± 54.46	23.40 ± 1.74A	0.133 ± 0.080BC ab
	10-20	5.32 ± 0.06	614.8 ± 8.89A	23.84 ± 1.38A	0.063 ± 0.031B b
	20-30	5.21 ± 0.09	699.4 ± 172.29	22.40 ± 0.93B	0.230 ± 0.139 a
R-Mb-M	0-10	5.55 ± 0.18	585.4 ± 73.83 a	24.48 ± 1.07A	0.033 ± 0.029C
	10-20	5.54 ± 0.18	404.0 ± 58.31B b	23.54 ± 1.55A	0.062 ± 0.060B
	20-30	5.42 ± 0.26	525.0 ± 85.39 a	24.50 ± 0.79A	0.176 ± 0.109

[a] *R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation.*

[b] *Different letters in each column denote statistically significant differences at P < 0.05 according to Duncan's multiple range test; Uppercase letters denote significant differences within each depth increment between the crop rotations; lowercase letters denote significant differences between the depth layers.*

Stratification of soil organic carbon (SOC) with depth was significantly influenced by cropping system (Figure 3.1a). The topsoil (0-10 cm) SOC content was significantly larger under the R-R-R rotation compared with rotations of rice with upland crops, while the opposite trend was seen for the 10-20 cm and 20-30 cm depth layers. When recalculated to SOC stocks per 10 cm depth increment a similar trend existed. Average SOC stocks were significantly greater in rice-upland crop rotation systems (R-M-R, R-Mb-R and R-Mb-M) than in the intensive rice monoculture treatment (R-R-R) for the 10-20 cm and 20-30 cm depth increments, but not for the 0-10 cm depth layer (Figure 3.2a).

The results also showed a stratification of the SOC stocks within each treatment with smaller SOC stocks for deeper depth increments. This was particularly the case in R-R-R, where SOC content at 10-20 and 20-30 cm depth significantly decreased to 38-53% as compared to the upper depth (Figure 3.2a). Total SOC over the entire 0-30 cm depth layer was significantly higher for the R-M-R and R-Mb-R rotations than under R-Mb-M or R-R-R.



(b)

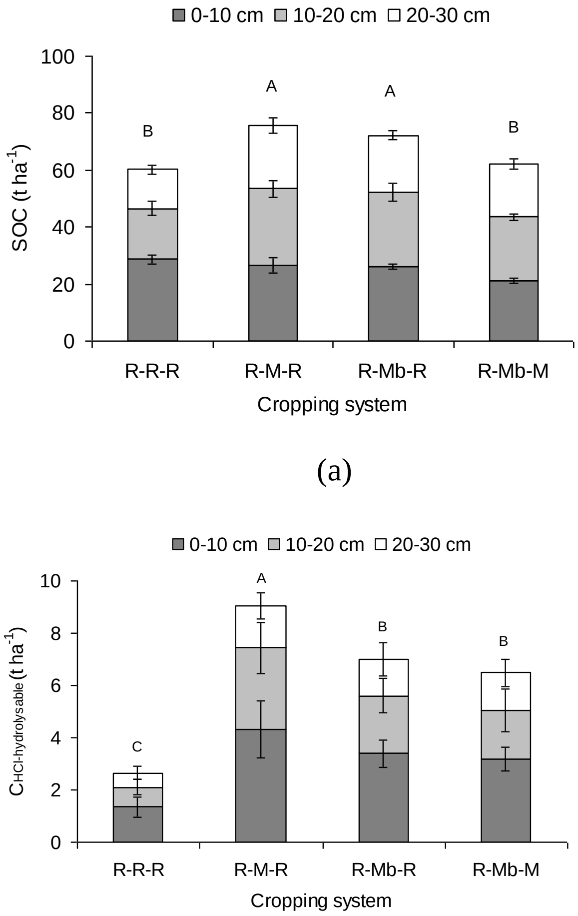
Figure 3. 1 Influence of cropping system on soil organic carbon (SOC) (a) and HCl hydrolysable carbon ($C_{hydrolysable}$) content (b) for three depth intervals.

R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation.

Different letters in adjacent columns within cropping system between the depth layers denote statistically significant differences at $P < 0.05$.

The $C_{hydrolysable}$ content significantly decreased with depth across all treatments and was significantly smaller in the rice monoculture rotation than in the other cropping system treatments (Figure 3.1b and 3.2b). Remarkably, over the 0-30 cm depth layer, stocks of $C_{hydrolysable}$ in rice-upland crop rotation systems were from two to three times greater than under R-R-R. Expressed as a relative fraction of

SOC, the proportion of $C_{hydrolysable}$ was 4.4% for R-R-R and more than twice that under the rice-upland crop rotation systems (9.7 – 11.9%) (Figure 3.3).



(a)

(b)

Figure 3. 2 Influence of cropping system on soil organic carbon (SOC) stocks (a) and HCl-hydrolysable soil C ($C_{hydrolysable}$) stocks (b) at 0-30 cm.

R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation.
Different letters in each column denote statistically significant differences at $P < 0.05$ between cropping systems.

All rotations with upland crops showed significantly greater rice straw yield than the intensive rice monoculture treatment. When comparing rotations of rice that included one or two upland crops (R-M-R, R-Mb-R, R-Mb-M) or rotations having different upland crops (R-M-R, R-Mb-R) no significant differences in rice straw yield were observed (Figure 3.4).

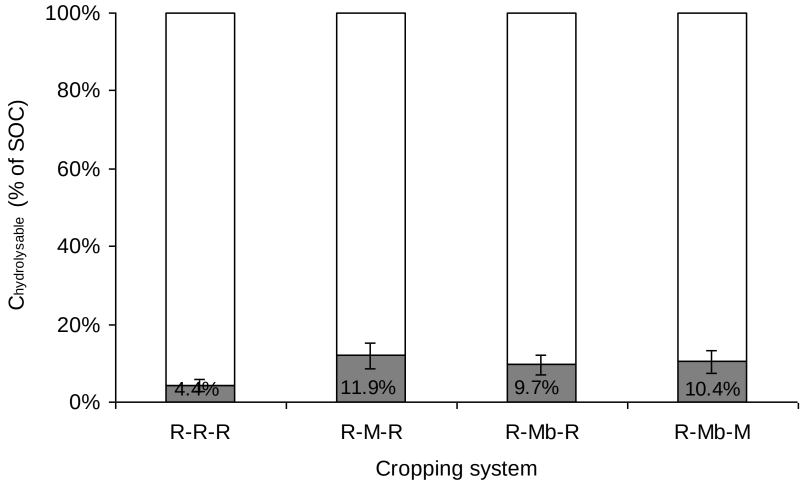


Figure 3. 3 Influence of cropping system on the percentage of the 0-30cm soil organic carbon stock that is hydrolysable in 6M HCl ($C_{hydrolysable}$).

R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation.

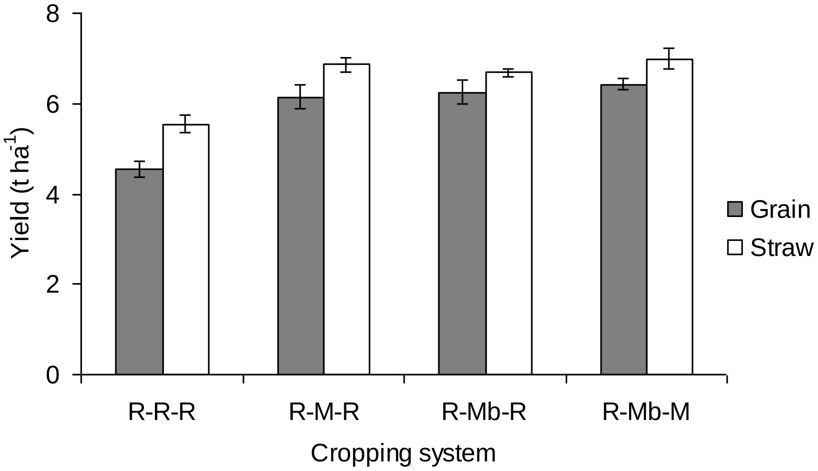


Figure 3. 4 Influence of cropping system on rice grain and straw yield.

R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation.

Analogous to rice straw yield, grain yield of rice was significantly affected by cropping system. It was lowest in R-R-R treatment, whilst the largest record was from R-Mb-M treatment (Figure 3.4). Rice yield in the rotations with upland crops was 35 to 42% higher (6.1-6.4 t ha^{-1}) compared with mono-cropped rice (4.5 tha^{-1}), but the differences between the three rotations with upland crops were not statistically significant.

3.4 Discussion

Over the eight consecutive cultivated years, cropping systems comprising rotations of rice and maize or mung bean (R-M-R, R-Mb-R and R-Mb-M) significantly raised topsoil (0-30 cm) CEC, SOC, $C_{hydrolysable}$ and reduced EC and soil total acidity compared to intensive rice monoculture (R-R-R). Despite higher amounts of TA in R-R-R, the soils did not show a lower pH. This can be explained by the high buffer capacity of the soil, owing to the very large clay content (~65%). For all treatments, CEC was medium to high (Brady and Weil, 2002) (between 21.2 and 24.5 cmol kg^{-1}). CEC increased with depth under monoculture rice cropping (R-R-R), although SOC decreased. The unexpected opposite evolutions of SOC and CEC with depth may be explained by progressively increasing clay content with depth in R-R-R (0-10 cm: 65%; 10-20 cm 68%; 20-30 cm: 70%) (Chapter 2). The reason for this increase in clay content is unknown but might be explained by a difference in clay content of the sediments deposited at different geological periods. Alternatively, it might be explained by downward movement of clay particles (Moorman and van Breemen, 1978; IRRI, 1985) with drainage of rain and irrigation water following soil dispersion caused by shallow puddling. In the cropping systems with rotations rice-upland crops on the other hand, small differences in clay content were probably removed during preparation of the temporary beds when soil was mixed. A significantly smaller SOC content but equal CEC for the 20-30 cm depth compared with the upper layers again points to the limited contribution of soil organic matter to soil CEC in these clayey soils.

After harvest, rice crop residues (roots + stubble) were left on the field. Flooding of the land every season in the case of R-R-R appears to have resulted in accumulation of organic matter, given the high 0-10 cm depth layer's SOC level (Figure 3.1a). Likely, the microbial decomposition of the fibrous residues was obstructed under anaerobic conditions prevailing under R-R-R, as has been reported before (Olk et al., 1995; 1996; 2009b; Kögel-Knaber et al., 2010). Guong et al. (2010) among others reported the specific accumulation of phenolic substances upon prolonged flooding. In line with these results, the 6M HCl-hydrolysable SOC fraction in the 0-10 cm layer was twice or three times lower in the R-R-R plots than in the rice-upland crop rotation systems, in spite of a much larger SOC content in that depth layer under monoculture rice (Figure 3.2b). It is well known that acid hydrolysis with HCl is particularly ineffective in degradation of phenolic compounds, i.e. lignin and other polyphenols. Resistance to acid hydrolysis is not only limited to lignin, but also is a common property of most of the more recalcitrant organic polymers like suberin, cutin and waxes. These findings support the view that topsoil SOC accumulation under R-R-R results from slowed decomposition of lignin-rich residues. This is consistent with results of Kanema (2009), who found greatest $C_{hydrolysable}$ under maize, followed by other upland crops, and a large decline in $C_{hydrolysable}$ under monoculture rice.

When making the temporary beds in treatments with upland crops, the rice residues were completely mixed with the soil till a depth of 20-30 cm, which most likely resulted in much less stratification of SOC than under mono-cropped rice (Figure 3.1a and 3.2a). Bulk density in R-R-R was significantly greater (25-46%) at depths of 10-20 and 20-30 cm compared to the topsoil (0-10 cm) but there were no differences in bulk density with depth under rice-upland crop rotations (Chapter 2). This demonstrates the clear differences in depth of soil mixing between the rice monoculture and rice-upland crop rotation systems.

The end result is that, although anaerobic degradation of rice residues is slowed in submerged soil, 0-30 cm SOC stocks were elevated in rice-upland crop rotations that involved shorter periods of inundation. Relocation of crop residues to deeper soil layers therefore seems to exert a very considerable control on the dynamics of the SOC in paddy soils. Recently, Don et al. (2013) demonstrated that distributing organic matter throughout a soil volume reduces its degradability. The larger SOC stocks at 0-30 cm under R-Mb-R and R-M-R systems were mainly due to greater SOC contents at 10-30 cm (Figure 2a), which is consistent with this theory. Yet, the apparent slowing of organic matter decomposition in the 10-30 cm layer could just as easily be related to diminished soil temperature or oxygen availability relative to the 0-10 cm layer above. In addition, an increased clay content or increased aggregation due to reduced tillage-induced disturbance of deeper layers could also explain accumulation of carbon relative to the topsoil. The current experimental layout did not allow for a conclusive analysis of these different hypotheses. Lastly, differences in organic matter supply through above- and belowground crop residues might be expected to explain the pronounced differences in 0-30 cm SOC stock between the crop rotations. However, nearly all above ground biomass from the upland crops was collected as feed for livestock after harvest and to facilitate land preparation for the next crop, resulting in a limited addition of crop residues to the soil. Indeed, the 0-30 cm SOC stock was significantly smaller in the case of the rotation with only one rice crop (R-Mb-M). The aerobic conditions during the two upland cropping seasons probably sped up mineralization of the limited supply of crop residues, as previously reported by Guong et al. (2010). We found no significant differences in SOC between the R-M-R and R-Mb-R crop rotation treatments at any studied depth, indicating no considerable differences in supply of stable organic carbon from either maize or mung bean.

In our study, $C_{hydrolysable}$ stock and proportion under the R-R-R system were smaller than under rice-upland crop rotation systems although SOC levels were highest in the 0-10 cm depth layer of the R-R-R system. Stine and Weil (2002) found that $C_{hydrolysable}$ influences the mass and activity of microbial species that have the capacity to release mineral nitrogen. Long-term flooding under rice cropping season (9–10 months for R-R-R compared with 3 months for R-Mb-M and 6 month for R-M-R and R-Mb-R) may have resulted in accumulation of organic materials as lignin and phenolic compounds form (Olk et al., 1996).

Becker et al. (1994) reported that enhancement of phenol content is recognized to restrict nitrogen mineralization of crop residues in flooded paddy soils. In addition, Devevre and Horwath (2001) reported that fertilizer nitrogen is also stabilized into soil organic matter fractions and it may influence mineral nitrogen release. It can be explained by an enhance in N binding to lignin-derived phenols under prolonged anaerobic decomposition of crop residues, which may reduce its bioavailability, and thus inhibiting its mineralization (Schmidt-Rohr et al., 2004; Olk et al., 2009b). This might be one of the main reasons why local farmers have to apply increasingly more nitrogen fertilizer year by year to maintain rice yields (Khoa, 2002). It should be noted that $C_{hydrolysable}$ content showed a pronounced diminishing depth gradient in the R-M-R, R-Mb-R and R-Mb-M objects while this was not the case for bulk SOC content (Fig. 3.1a and b). This might be explained by the relatively better root distribution and higher biological stability of the soil organic matter in the subsoil compared to the 0-10 cm layer.

There were no differences in pH across the cropping system treatments. This can be explained by the high pH buffering capacity of these relatively young clayey soils of the Mekong floodplain. In contrast to pH, TA was less in rotations including upland crops than under monoculture rice. During field inundation for the rice cropping season, organic residues decompose under anaerobic conditions, which may produce toxic H_2S, hence increase total acidity (Hung, 2009). Generally, saline soils are defined as those having an EC_e value > 4 dS m^{-1} (Brady and Weil, 2002; Hazelton and Murphy, 2007). As EC_e was not determined in our study, we estimated it from the measured $EC_{1:5}$ values using a conversion factor of 6.3, a factor based on previous data of topsoil $EC_{1:5}$ and EC_e collected by Khoa (2002) in the same study location to our experiment. This value was close to 5.8 found by others for heavy clay textured soil (Slavich and Petterson, 1993; Hazelton and Murphy, 2007). Overall, the average EC_e value of the top 30 cm in all treatments varied from 3.2 to 4.3 dS m^{-1}, and thus the soil can be classified as none-saline to slightly saline. The lower EC in the specific case of the R-Mb-M treatment might be explained by the salts being washed out from the soil because of the better drainage associated with the preparation of temporary beds for the two upland crops.

Cropping systems of rice and upland crop rotations with temporary beds could correct for subsoil compaction resulting from long-term intensive rice mono cultivation (Chapter 2). Also SOC and $C_{hydrolyzable}$ were significantly improved when introducing mung bean and maize in rice cropping systems as discussed above. The higher soil quality might have explained the higher rice grain and straw yields observed in rotation of rice with upland crops system in subsequent season (Figure 3.4).

3.5 Conclusions

This study revealed improved chemical soil fertility in cropping systems with rotations of rice and upland crop compared to rice monoculture. As a consequence, also rice grain and straw yield was improved and hence their inclusion in rice-based systems is recommended. Long-term rotations of rice with upland crops on alluvial soils with heavy clayey texture also strongly affected the depth stratification of SOC and $C_{hydrolysable}$. Unlike the top 10 cm, almost all these parameters significantly improved at depths of 10-20 cm and 20-30 cm when rotating rice with upland crops. The storage of SOC under rice-upland crop rotation systems seems to be unlikely caused by an enhanced organic matter supply but rather relates somehow to deeper mixing of soil and burial of crop residues. It would appear that under two upland crops (R-Mb-M) the doubled duration of aerated soil conditions and enhanced microbial degradation of crop residues and SOM is causing lower SOC levels compared to the R-M-R or R-Mb-R rotations with one upland crop. This experiment stresses the need for depth differentiated soil sampling and analysis with recording of soil bulk density in any such effort to compare paddy soil rice monoculture and rice-upland crop rotation systems.

Chapter 4

Annual rice-upland cropping systems result in improved root growth, rice yield and economic profit relative to rice monoculture in late wet season[#]

This chapter is based on:

Linh, T.B., Sleutel, S., Guong, V.T., Khoa, L.V., Cornelis, W.M., 2015. Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture. Soil & Tillage Research 154, 44-52.

4.1 Introduction

In riverine floodplain areas worldwide, rice monoculture is intensifying towards double or triple annual rice crops. Continuous intensive monocultures of rice can lead to subsoil compaction, reduced topsoil quality and decline in rice yield. Because of long-term submergence, continuous rice growing has been found to yield an adverse impact on soil nitrogen supply (Pulleman et al., 2000; Norman et al., 2003), which can negatively affect agricultural sustainability (Dobermann and Witt, 2000). A few studies employing ^{15}N NMR spectroscopy found prolonged anaerobic decomposition of crop residues to enhance N binding to lignin-derived phenols, which may inhibit its mineralization (Schmidt-Rohr et al., 2004; Olk et al., 2007, 2009b).

Soil puddling under saturated conditions with machinery is the standard soil preparation in lowland rice cultivation. After prolonged rice cultivation a 10-50 cm plow layer (or hard pan) is thus formed below the puddle layer, preventing ponding water to drain further downward (Liu et al., 2001). While it limits water losses, subsoil compaction can be a major crop growth constraint in intensively cultivated paddy fields with clay soils being most susceptible (Gay et al., 2009). It limits rooting depth and root exploration (Rosolem et al., 2002), which might result in reduced uptake of water and nutrients (Bingham et al., 2010; Lipiec and Hatano, 2003).

In the Vietnamese Mekong Delta, where this study was conducted, soil quality for sustainable rice production is under considerable pressure, as in similar settings worldwide. Effects of different cropping systems with rotations of rice and upland crops like maize and mung bean on soil properties in the spring-summer season, i.e. the dry season when rice, maize or mung bean are cultivated, have been previously reported in Chapter 2 and 3. They showed an improvement of soil bulk density, soil strength, soil porosity, soil organic carbon, $C_{hydrolyzable}$ for cropping system with rotations of rice and mung bean and/or maize grown on temporary beds compared to intensive rice monoculture.

We hypothesize that growing upland crops as maize (*Zea mays* L.) and/or mung bean (*Vigna radiata* (L.) R. Wilczek) instead of rice (*Oryza sativa* L.) as in rice monocultures positively affect root growth and yield of rice grown in a subsequent season because of improved soil properties. The objective of this paper was to evaluate the effects of rotating rice with upland crops on soil properties at harvest in the winter–spring season, i.e. the late wet rice season, and to investigate how this affects yield components and yield of rice. The combination of a shallow puddle layer and triple annual crop exports bears an explicit risk of nutrient deficiency due to shallow rice rooting, an important parameter most often overlooked. Deeper tillage common in upland crops like maize and mung bean should loosen topsoil layers and allow for enhanced root growth and availability of nutrients, thus improving rice yield. At the same time, however, breaking up the plow pan of any paddy soil may result in irrigation water and dissolved nutrient losses, with on the opposite a detrimental effect on rice yields. In addition, with chemical fertilizer and pesticide use, paddy fields are considered to be the potential source of pollutants for water bodies. The present study measured a suite of soil physical and chemical traits after completion of a 10 year field experiment in the Vietnamese Mekong Delta with rice monoculture and three rice upland crop rotations. We explicitly determined rice root biomass within depth increments to assess the impact thereupon of upland crop inclusion in paddy rice based rotations. Evidently, economic benefit would be an important criterion for shifting from rice monoculture to new crop rotation systems with upland crops, and therefore net return and benefit-cost ratio was investigated as well.

4.2 Material and methods

4.2.1. Site description and field experiment

Site description and field experiment was previously presented in Chapter 1 section 1.5.

4.2.2. Soil sampling and crop measurements

In the winter–spring season, rice was cultivated in all treatments. The beds of the prior season were removed and the soil surface was levelled. Samples were thus taken at the same soil depth for all treatments. Soil sampling and field measurements took place one day before rice was harvested in all treatments at the end of the winter–spring cropping season of the tenth experimental year. Detail of soil sampling procedure was previously presented in Chapter 2 section 2.2.2.

For rice crop measurement, at harvest four subplots of 5 m^2 were harvested per cropping system and yield was standardized to tonnes ha^{-1} of total grain (14% moisture base) and straw dry matter yield. The grain yield relative to that of the R–R–R (control = 100%) treatment was calculated for each crop rotation treatment. The height of rice, thousand grain weight, filled grain, grain per panicle and panicle number were determined from plants harvested from a sample area of 0.5 m^2 per subplot. Maximum rooting depth was determined per subplot by digging out and uprooting a single plant near its base after which the length of the longest root was recorded. Root biomass was determined on soil cores with two replicates per plot. To this end, a 30 cm deep cylindrical core with 10 cm diameter was pushed into the soil to collect an undisturbed soil sample. These soil samples were separately washed and roots separated using a set of sieves with mesh sizes from 1 to 0.05 mm after they were cut once for 10 cm depth increment starting from the soil surface. Then roots were oven dried at 105 °C and their dry weight recorded. The root mass density was calculated by dividing mass of root by total volume of soil.

4.2.3. Soil physical and chemical properties

The procedures used for soil physical and chemical analysis such as soil bulk density, particle density, total porosity, plant available water capacity, aggregate stability, pH, EC, CEC, total acidity, soil organic carbon, carbon hydrolysable were described in Chapter 2 and Chapter 3.

Macro porosity (MacP), defined as the volume of pores with pore neck > 0.3mm, was calculated as: MacP = θ_s – MatP, where θ_s (m^3 m^{-3}) is the saturated volumetric water content of the soil matrix and MatP is matric porosity, MatP = θ_m, where θ_m the volumetric water content at matric potential of –1 kPa according to Reynolds et al. (2007).

4.2.4. Economic profitability performance

According to Senkondo et al. (2004), economic analysis can provide information about the sustainability of a practice for increased productivity and enhanced resource use efficiency in a given period. Therefore, total cost, total income, total profit and benefit-cost analysis was carried out to compare the economic feasibility of the new cropping systems. The crop grain yield values form the gross income, while the total costs included the cost for seed, fertilizer, pesticide, herbicide, and labor for land preparation, seeding, sowing fertilizer, spraying pesticides, weeding, irrigation, harvesting, and post harvest operations (storage, transportation). The 2012 market price of each crop’s grain was obtained from the Department of Agriculture in Cai Lay district. The economic benefit was calculated based on a 1 ha field during the crop cycle year 2011–2012. A benefit–cost ratio, which indicates the rate of return per unit of cost, was calculated as the divide between total income and total cost (Ramji and Gopal, 2001; Golam and Gopal, 2006). Benefit–cost ratio greater than 1 indicates that a cropping system is profitable.

4.2.5. Data analysis

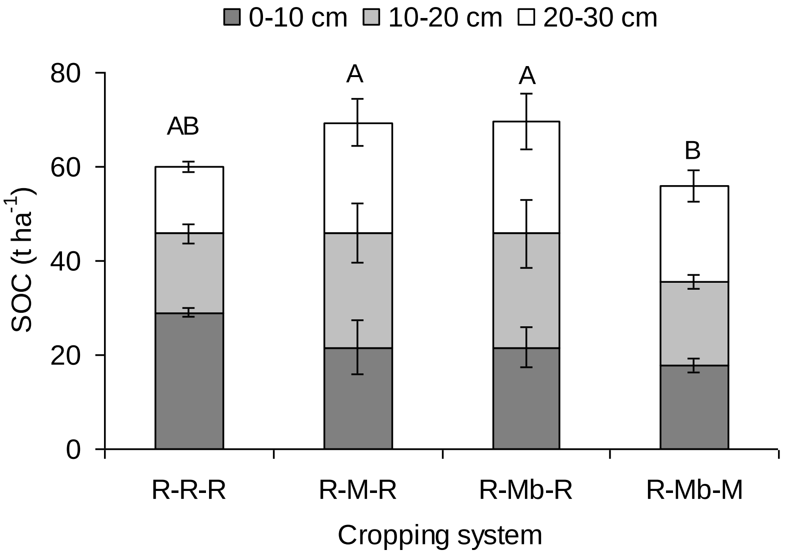
Analysis of variance (ANOVA) was conducted on all the agronomic parameters and soil properties with crop rotation and depth layer as fixed factors. Significant differences amongst individual depth increments or crop rotations were determined using Duncan's multiple range test ($P < 0.05$). All statistical analyses were carried out with SPSS 20.0 (IBM Corp., 2011).

4.3 Results

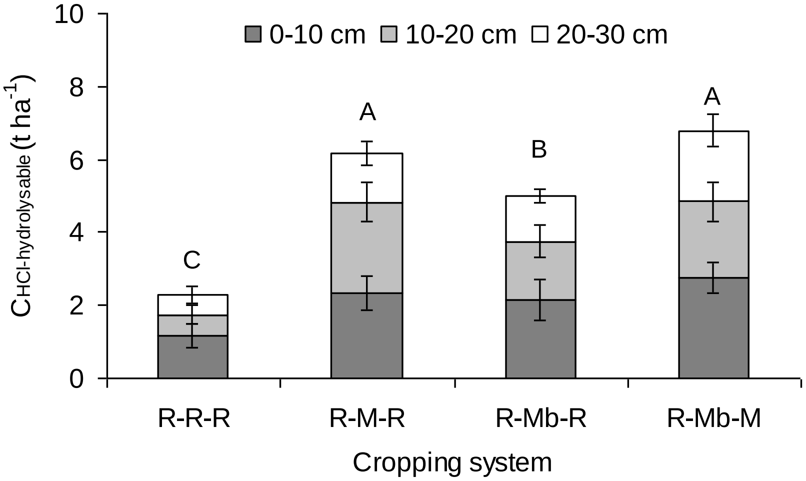
4.3.1 Soil chemical properties

Soil pH ranged from 5.4 to 5.6 and was not significantly different between depths or cropping systems (Table 4.1). EC ranged between 474 and 653 $\mu S\ cm^{-1}$ (Table 4.1) and was not significantly different between depths, while EC at 0–10 and 10–20 cm depth was significantly lower ($P < 0.05$) in rotation systems with upland crops than in rice monoculture, except for R–M–R where the lower value was not significant. TA at 0–10 cm depth was significantly lower in the R–Mb–M rotation compared to other treatments, while no significant differences existed at 10–20 and 20–30 cm depth. Topsoil (0–10 cm) CEC was significantly higher ($P < 0.05$) under R–M–R, R–Mb–R and R–Mb–M compared to R–R–R (Table 4.1) with no differences for the underlying layers. Across the three depth intervals, CEC increased significantly in R–R–R with depth ($P < 0.05$).

SOC stocks of all three depth increments differed significantly ($P < 0.05$) between the crop rotations (Fig 4.1a). It was lower under rice monoculture compared to rotations with upland crops at depths of 10–20 and 20–30 cm but on the opposite the 0–10 cm SOC stock was significantly higher. At all depths $C_{hydrolyzable}$ stocks were significantly higher in rice–upland crop rotations compared to rice monoculture (Fig. 4.1b).



(a)



(b)

Figure 4. 1 Influence of cropping system on soil organic carbon (SOC) (a) and 6 M HCl-hydrolysable soil C stocks ($C_{hydrolysable}$) (b) at 0–30 cm as measured after rice harvest at the end of the winter–spring cropping season of the tenth experimental year.

R–R–R, rice–rice–rice monoculture; R–M–R, rice–maize–rice rotation; R–Mb–R, rice–mung bean–rice rotation; R–Mb–M, rice–mung bean–maize rotation. Different letters in each bar denote statistically significant differences at $P < 0.05$ between cropping systems.

Table 4. 1 Influence of crop rotation on soil properties for four cropping systems at three depths as measured after rice harvest at the end of the winter-spring cropping season of the tenth experimental year [1]

Cropping system	Depth (cm)	pH (-)	EC (µS cm^{-1})	CEC (cmol+ kg^{-1})	TA (cmol kg^{-1})	PD (Mg m^{-3})	SP (%)	MacP (m^{3} m^{-3})	PAWC (m^{3} m^{-3})	SI (-)
R–R–R	0–10	5.43 ± 0.15	653 ± 65^{A}	$21.74 \pm 0.55^{B}_{b}$	0.490 ± 0.155^{A}	$2.39 \pm 0.04^{B}_{b}$	$62.05 \pm 0.98_{a}$	$0.0371 \pm 0.0024^{B}_{a}$	$0.239 \pm 0.026_{a}$	$1.42 \pm 0.16^{C}_{a}$
	10–20	5.48 ± 0.23	637 ± 71^{A}	$22.02 \pm 0.95_{b}$	0.389 ± 0.229	$2.48 \pm 0.03_{a}$	$54.19 \pm 2.38^{B}_{b}$	$0.0346 \pm 0.0037^{B}_{a}$	$0.231 \pm 0.040_{a}$	$1.14 \pm 0.19^{B}_{a}$
	20–30	5.56 ± 0.16	620 ± 53	$24.21 \pm 1.01^{A}_{a}$	0.308 ± 0.234	$2.52 \pm 0.02_{a}$	$47.87 \pm 1.88^{B}_{c}$	$0.0228 \pm 0.0072^{B}_{b}$	$0.167 \pm 0.018^{B}_{b}$	$0.79 \pm 0.10^{B}_{b}$
R–M–R	0–10	5.49 ± 0.21	611 ± 59^{AB}	23.23 ± 0.93^{A}	0.414 ± 0.175^{A}	$2.40 \pm 0.07^{B}_{b}$	$62.85 \pm 0.83_{a}$	0.0539 ± 0.0090^{A}	0.245 ± 0.016	1.76 ± 0.25^{BC}
	10–20	5.61 ± 0.21	604 ± 62^{AB}	23.38 ± 1.26	0.236 ± 0.095	$2.46 \pm 0.02_{a}$	$58.60 \pm 0.89^{A}_{b}$	0.0470 ± 0.0064^{A}	0.236 ± 0.014	1.90 ± 0.15^{A}
	20–30	5.51 ± 0.20	589 ± 56	22.13 ± 0.89^{B}	0.269 ± 0.154	$2.51 \pm 0.03_{a}$	$56.73 \pm 1.83^{A}_{b}$	0.0450 ± 0.0035^{A}	0.258 ± 0.025^{A}	2.00 ± 0.24^{A}
R–Mb–R	0–10	5.44 ± 0.21	544 ± 34^{BC}	23.13 ± 0.91^{A}	0.367 ± 0.183^{AB}	2.43 ± 0.04^{B}	62.02 ± 2.12	0.0505 ± 0.0071^{AB}	0.244 ± 0.014	2.04 ± 0.19^{AB}
	10–20	5.52 ± 0.25	540 ± 65^{B}	23.45 ± 0.66	0.261 ± 0.131	2.48 ± 0.03	58.89 ± 4.54^{A}	0.0509 ± 0.0046^{A}	0.258 ± 0.017	2.02 ± 0.13^{A}
	20–30	5.53 ± 0.16	524 ± 87	22.98 ± 0.83^{AB}	0.164 ± 0.089	2.47 ± 0.06	55.34 ± 2.73^{A}	0.0506 ± 0.0089^{A}	0.263 ± 0.023^{A}	1.99 ± 0.36^{A}
R–Mb–M	0–10	5.60 ± 0.17	459 ± 71^{C}	24.00 ± 0.89^{A}	0.172 ± 0.168^{B}	2.49 ± 0.03^{A}	$59.99 \pm 2.30_{a}$	0.0446 ± 0.0088^{AB}	0.262 ± 0.020	2.29 ± 0.38^{A}
	10–20	5.57 ± 0.22	520 ± 53^{B}	23.51 ± 1.19	0.148 ± 0.100	2.45 ± 0.05	$59.67 \pm 2.91^{A}_{a}$	0.0554 ± 0.0119^{A}	0.261 ± 0.007	2.01 ± 0.37^{A}
	20–30	5.59 ± 0.30	474 ± 112	23.73 ± 1.03^{AB}	0.270 ± 0.193	2.46 ± 0.04	$56.36 \pm 2.25^{A}_{b}$	0.0496 ± 0.0081^{A}	0.250 ± 0.018^{A}	2.12 ± 0.41^{A}

[1] *R─R─R, rice─rice─rice monoculture; R─M─R, rice─maize─rice rotation; R─Mb─R, rice─mung bean─rice rotation; R─Mb─M, rice─mung bean─maize rotation. EC, electric conductivity; CEC, cation exchange capacity; TA, total acidity; PD, soil particle density; SP, soil porosity; MacP, macro-porosity; PAWC, plant available water capacity; SI, soil aggregate stability index . Different letters in each column mean statistically significant differences at $P < 0.05$ using Duncan's multiple range test; A, B and C are the significant differences between the treatments of each depth; a and b are the significant differences between the depths within treatment. Numbers following ± symbol represent the standard deviations*

Table 4. 2 Effect of crop rotation on plant height, thousand-grain weight, filled grain percentage, number of grain per panicle, number of panicle, rooting depth, root mass density and rice straw and grain yield as measured after rice harvest at the end of the winter–spring cropping season of the tenth experimental year [1]

Cropping system	Plant height (cm)	Thousand-grain weight (g)	Filled grain (%)	Grain per panicle	Panicle no. m^{-2}	Rooting depth (cm)	Root mass density (g m^{-2})	Straw yield (tonnes ha^{-1})	Grain yield (tonnes ha^{-1})
R–R–R	65.4b	26.72^{ns}	72.06^{ns}	41.60b	729b	19.0b	91.11b	5.7b	4.80b
R–M–R	73.6a	26.77	72.33	46.50a	887a	26.3a	154.60a	7.0a	6.33a
R–Mb–R	73.8a	26.74	69.66	48.05a	866a	26.1a	147.80a	7.1a	6.30a
R–Mb–M	74.5a	26.73	69.88	46.22a	895a	27.2a	156.15a	7.3a	6.52a

[1] *R─R─R, rice─rice─rice monoculture; R─M─R, rice─maize─rice rotation; R─Mb─R, rice─mung bean─rice rotation; R─Mb─M, rice─mung bean─maize rotation. Different letters within columns denote statistically significant differences at P < 0.05 using Duncan's multiple range test; ns: no significant differences.*

4.3.2 Soil physical properties

Bulk density increased significantly with depth in all cropping systems and was affected by cropping system (Fig. 4.2). At a depth of 0–10 cm, bulk density was significantly higher in the rotation of rice with two upland crops (R–Mb–M) as compared to the other three rotations. At 10–20 cm and 20–30 cm depth, bulk density was significantly higher under R–R–R than in the other crop rotations.

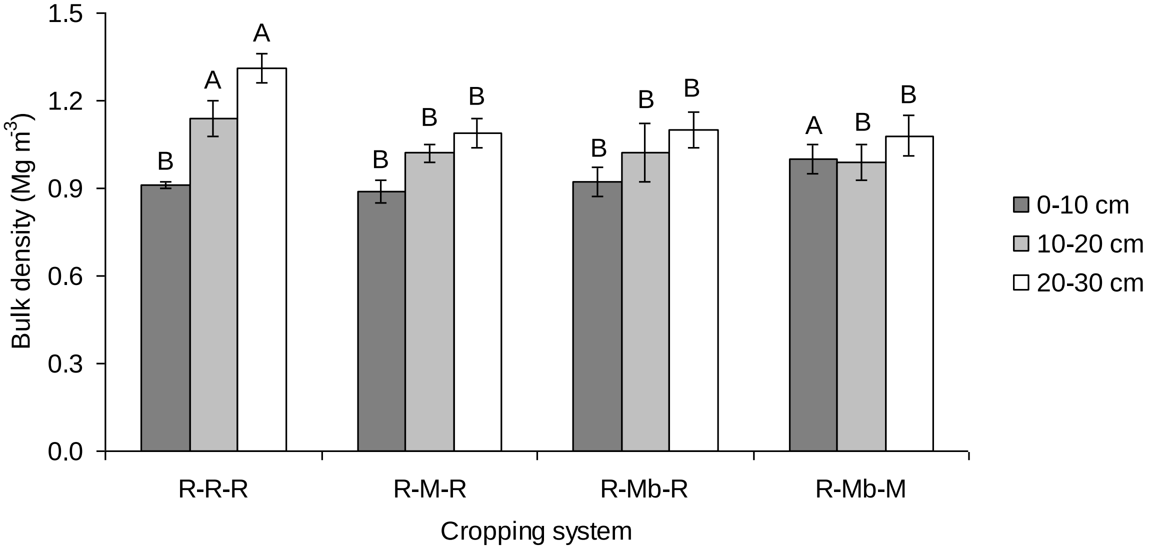


Figure 4. 2 Influence of cropping system on soil bulk density as measured after rice harvest at the end of the winter–spring cropping season of the tenth experimental year.

R–R–R, rice–rice–rice monoculture; R–M–R, rice–maize–rice rotation; R–Mb–R, rice–mung bean–rice rotation; R–Mb–M, rice–mung bean–maize rotation. Bars represent standard deviations for each cropping system.
Different letters within each depth layer denote statistically significant differences ($P < 0.05$) among the cropping systems.

Soil porosity was higher in the three rice upland crop rotations compared to R–R–R at 10–20 and 20–30 cm depth. Soil porosity was also significantly lower in these depth increments compared to the 0–10 cm layer in case of the R–R–R, R–M–R and R–Mb–R rotations (Table 4.1).

At depth of 20-30 cm, MacP and PAWC were significantly lower in the R–R–R treatment compared to the rice-upland crops rotations (Table 4.1). In the top 0–10 cm and 0–20 cm little differences were present between the treatments for MacP and PAWC, respectively.

Profiles of penetration resistance showed no significant differences at depths shallower than 10 cm and greater than 45 cm (Fig. 4.3) between cropping systems. However, soil strength between 15 and 45 cm depth as indicated by penetration resistance, was significantly ($P < 0.05$) lower in the rice-upland crop rotations compared with R–R–R.

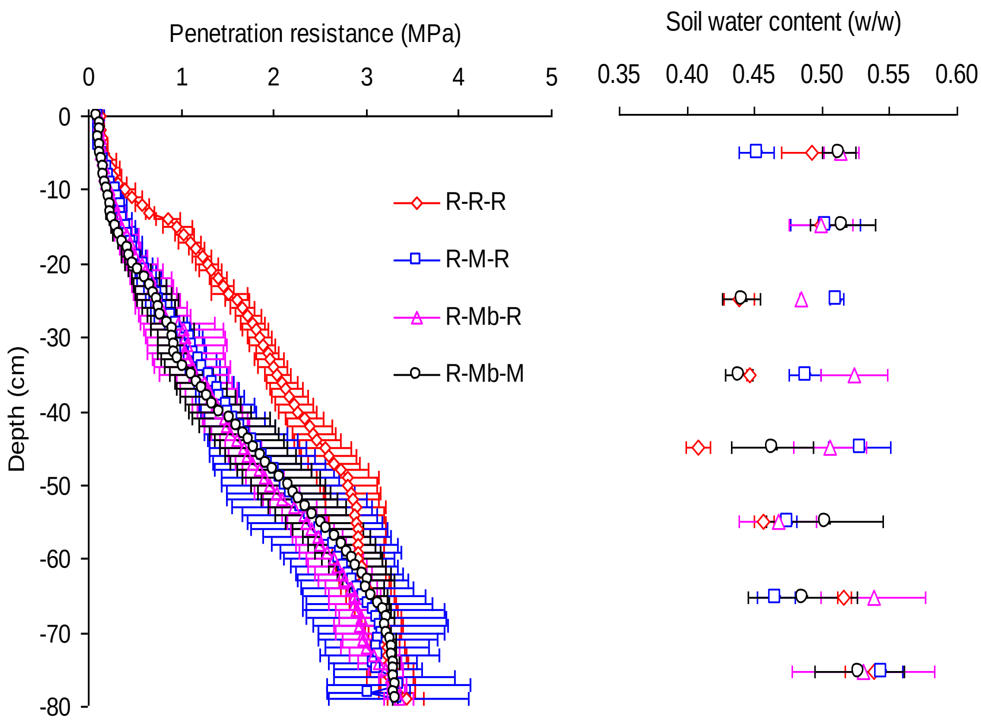


Figure 4. 3 Soil strength and corresponding soil water content averaged over four replicates in rice–rice–rice (R–R–R), rice–maize–rice rotation (R–M–R), rice–mung bean–rice rotation (R–Mb–R), rice–mung bean–maize rotation (R–Mb–M). Both were measured after rice harvest at the end of the winter–spring cropping season of the tenth experimental year. Bars represent standard deviations for each cropping system (n = 4).

Rice rotation with maize and mung bean (R–M–R, R–Mb–R and R–Mb–M) nearly always increased the soil aggregate stability index (SI) compared to the control treatment R–R–R by 26–50%, 41–63% and 82–131% at depth of 0–10, 10–20 and 20–30 cm, respectively. Only under R–R–R, the SI differed significantly with depth, with a lower value for the 20–30 cm depth than in the upper lying layers (Table 4.1).

4.3.3 Yield components and rice yield

In all three rotations with upland crops rice height, grain per panicle, panicle per square meter, rooting depth and root mass density were significantly ($P < 0.05$) higher than in the rice monoculture treatment. A closer look to root mass density reveals that they are most abundant in the top 0–10 cm (67–72%) for all rotations with upland crops, and depth increment 10–20 cm and 20–30 cm only contain 20–24% and 7–9% roots, respectively (Fig. 4.4). In case of R–R–R, roots are only present in the depth increments 0–10 cm (84–88%) and 10–20 cm (12–16%). The 1,000 grain weight and the full grain percentage were not significantly different among the treatments (Table 4.2) nor were there differences in any of these parameters amongst the rice-upland crop rotations (Table 4.2).

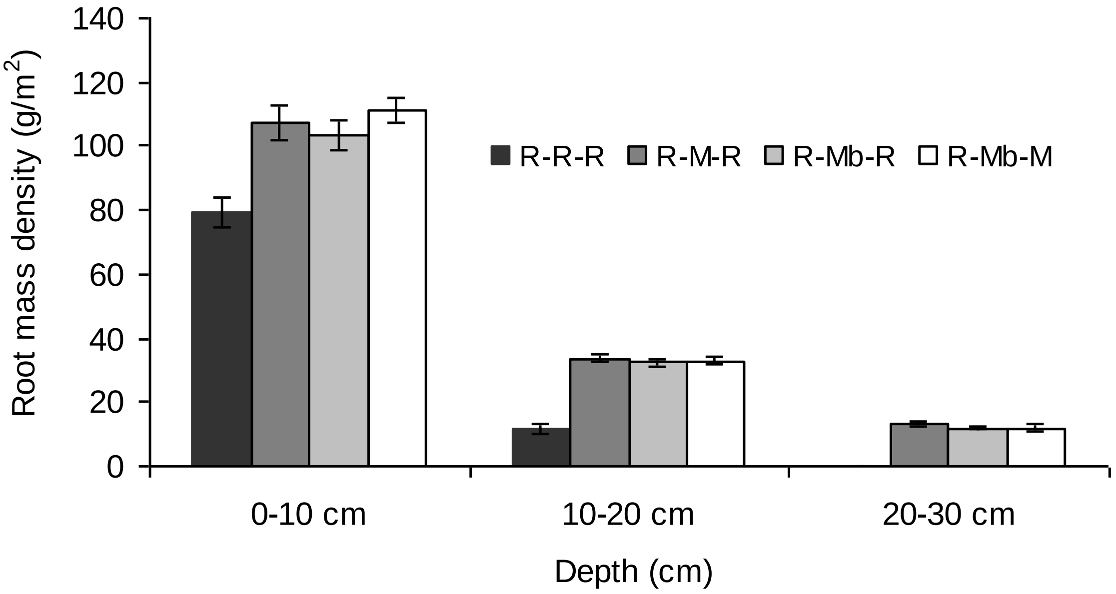


Figure 4. 4 Influence of cropping system on root mass density of rice as measured at the end of the winter-spring cropping season of the tenth experimental year.

R–R–R, rice–rice–rice monoculture; R–M–R, rice–maize–rice rotation; R–Mb–R, rice–mung bean–rice rotation; R–Mb–M, rice–mung bean–maize rotation.

Grain yield of rice was significantly affected by cropping system. It was 30–35% lower under R–R–R compared to the other crop rotations (Table 4.2), amongst which differences were minor. Rice straw yield (Table 4.2) and average grain yield in the winter–spring and summer–autumn season from 2002 till 2012 (Fig. 4.5) showed similar trends. The mean rice yield was significantly higher for winter–spring than for summer–autumn cropping period. The reduction of rice yield in summer-autumn compared to winter-spring season may be due to increase in daily rainfall and decrease in sunshine hours during reproductive and grain filling phases. Moreover, the pollination of rice is limited in the rainy season and pests and diseases are more prevalent.

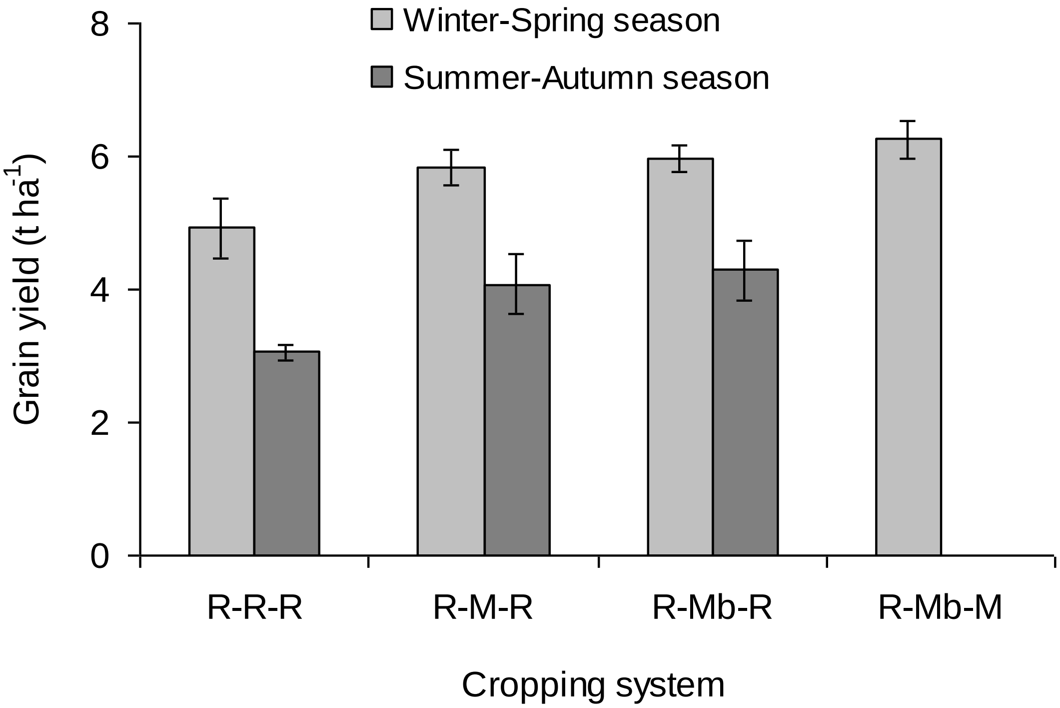


Figure 4. 5 Average rice grain yield from 2002 till 2012 in the winter–spring and summer–autumn season of the long-term filed experiment at Cai Lay district.

rice–rice–rice (R–R–R), rice–maize–rice rotation (R–M–R), rice–mung bean–rice rotation (R–Mb–R), rice–mung bean–maize rotation (R–Mb–M). Bars represent standard deviations for each cropping system.

4.3.4 Crop rotation influence on economic feasibility

Table 4.3 shows the total costs on the one hand (input) and income on the other (output) with total profit and cost–benefit ratio for the different cropping systems and cropping seasons, and for a complete agricultural year. The results show that the total cost of rice–upland crop rotation systems (R–M–R, R–Mb–R and R–Mb–M) was significantly higher than that of the R–R–R system. However, practicing rice monoculture clearly results in a much lower farm income per hectare than when applying a rotation farming system. The total income doubled for R–Mb–M or nearly doubled for the R–M–R and R–Mb–R treatments compared to R–R–R.

Table 4. 3 Total cost of cultivation, gross return, net return and benefit–cost ratio of different rice-based cropping systems (in USD ha^{-1}) in the tenth experimental year [1]

Crop season	Cropping system	Crop cultivation	Total cost cultivation	Gross return	Net return	B/C ratio
Summer–Autumn 2011	R–R–**R**	Rice	712b	882c	169c	1.24c
	R–M–**R**	Rice	712b	1,048b	335b	1.47b
	R–Mb–**R**	Rice	712b	1,085b	372b	1.52b
	R–Mb–**M**	Maize	1,085a	2,013a	928a	1.86a
Winter–Spring 2011–2012	**R**–R–R	Rice	654a	1,263b	609b	1.93b
	R–M–R	Rice	654a	1,663a	1,008a	2.54a
	R–Mb–R	Rice	654a	1,661a	1,007a	2.54a
	R–Mb–M	Rice	654a	1,716a	1,062a	2.62a
Spring–Summer 2012	R–**R**–R	Rice	739c	835c	96c	1.13b
	R–**M**–R	Maize	1,097a	2,016a	919a	1.84a
	R–**Mb**–R	Mungbean	845b	1,455b	610b	1.72a
	R–**Mb**–M	Mungbean	845b	1,429b	584b	1.69a
Whole agricultural year 2011–2102	R–R–R		2,106d	2,982d	875d	1.42b
	R–M–R		2,464b	4,727b	2,263b	1.92a
	R–Mb–R		2,212c	4,202c	1,990c	1.90a
	R–Mb–M		2,584a	5,159a	2,575a	2.00a

[1] *Mean with a same letter in a same column and crop season are not significantly different at P < 0.05 probability level. R–R–R, rice–rice–rice monoculture; R–M–R, rice–maize–rice rotation; R–Mb–R, rice–mung bean–rice rotation; R–Mb–M, rice–mung bean–maize rotation. B/C, benefit–cost ratio*

Regarding the total profit (net return), differences among the cropping systems was very large. The total profit was about tripled for rice rotated with maize and mung bean, and more than doubled when rotating rice with maize or mung bean, as compared to intensive rice monoculture. Accordingly, the benefit–cost ratio of rice-upland crop rotation systems was higher than that of traditional rice monocultures, with rotations of rice with two upland crops (R–Mb–M) economically being most efficient.

4.4 Discussion

The rice yield of the different crop rotations was in the following order: R–R–R < R–Mb–R = R–M–R = R–Mb–M ($P < 0.05$). The improved yield under rice upland crop rotation was accompanied by greater rice height, number of grains per panicle, and panicle number. These results are consistent with several other studies demonstrating rice yield increases with upland crop inclusion in rice based rotations (Filizadeh et al., 2007; Song et al., 2012; Xuan et al., 2012; Mandal et al., 2014).

Introduction of maize or/and mung bean in rice monoculture influenced several important soil properties positively (Table 4.1 and Fig. 4.3). Though insignificantly, upland crop inclusion raised the soil pH and lowered the EC compared to R–R–R. In all rotations EC values denoted non-saline conditions and pH values were optimal for rice (Sys et al., 1993) ensuring maximum nutrient availability, and the soils were thus generally suitable for crop growth (Fageria and Baligar, 1999; Issaka et al., 2004). Variations of rice yield in this study are probably not explained by variation in pH, EC, or TA because variation in these soil properties was minimal. It should be noted that the current pH measurements are thus only relevant to soil fertility for the subsequent upland crop and have little or no relevance for the growth of rice because in paddy fields, pH will always evolve towards neutrality after few weeks of submergence.

Our findings also showed these higher rice yields under R–Mb–R or R–M–R to coincide with increased stocks of SOC in spite of lower bulk density, and a higher degree of $C_{\text{hydrolysable}}$. Lower rice and straw yields in the pro-longed rice monoculture compared to R–Mb–R, R–M–R (Table 4.2) firstly logically explain lower SOC levels in the former. The absence of a deeper mixing tillage in monoculture rice in addition likely resulted in specific lower crop residue C input into the 10–20 and 20–30 cm depth (Chapter 3). This would explain their higher SOC stock in the R–M–R and R–Mb–R rotations. On the other hand, the total annual period with aerobic soil conditions is longer in the rice-upland crop rotations, i.e. the maize or mung bean seasons, during which organic matter decomposition should be promoted, with consequent lower SOC levels. Indeed, in the R–R–R system, rice residues remained visibly un-decomposed from one rice-growing season to the next, which was not the case in the rice-upland crop rotations. This confirms previous reports that anaerobic conditions reduce decomposition of organic residues by Pulleman et al. (2000) and Norman et al. (2003). In line, Motschenbacher et al. (2011) indicated that instead, frequent cycling between anaerobic (flooding) and aerobic condition (none flooding) of rice and upland crop rotation can result in a greater rate of organic manure decomposition. In addition, a change in soil organic matter quality was denoted by the much lower fraction of 6 M HCl hydrolysable C in the R–R–R rotation compared to the others, suggesting a relative higher biological stability of the soil organic matter under continuous intensive rice. In contrast to all of this as explained above, the 10–30 cm SOC stocks were nonetheless higher under the R–M–R and R–Mb–R rotations than under R–R–R (Fig. 4.1). This seemingly contradictory result may be explained if we assume that the increased crop productivity and related C-inputs in these rice-upland crop rotations must have exceeded increases in annual soil C-mineralization compared to triple rice cropping. In case of R–Mb–M, the non-irrigated period was even longer and it would appear that the resulting increased loss of C by prolonged aerobic soil organic matter decomposition was in balance with the higher root-C biomass inputs. Consequently, there was no SOC accumulation under the R–Mb–M compared to the R–R–R crop rotation.

Higher diversity of soil microbiological communities and activities due to SOC storage in crop rotation systems similar to our experiment have been reported to result in an increase of rice yield (Dung et al., 2010; Dung, 2012; Xuan et al., 2012). Hence, it might be argued that elevated SOC levels favored soil nitrogen supply (Stine and Weil, 2002), which in turn would have increased rice crop yields under R–Mb–R and R–M–R.

However, this reasoning would not hold for the R–Mb–M rotation, where SOC levels remained at a pair with the R–R–R treatment and other explanations need to be looked at. As will be discussed below reduced root penetration must additionally have restricted root-derived C inputs into the 20-30 cm depth under R–R–R.

One of the main positive effects of inclusion of upland crops in a previously monoculture managed paddy field was the lifting of soil compaction in the 10–30 cm depth layer, as was clear from a marked drop in bulk density from 1.3 Mg m^{-3} under R–R–R to just 1.0 Mg m^{-3} and in addition by a nearly halving of the penetration resistance (Fig. 4.3). As a consequence, roots were found to grow deeper and more densely (Table 4.2 and Fig. 4.4). This should have resulted in better nutrient availability and plant uptake, as was indirectly suggested by improved rice yields. Under R–R–R on the contrary, the frequent puddling till 10–15 cm depth maintained the existing shallow plow pan, already starting from 10 cm downwards (Fig. 4.3). The bulk density at 20–30 cm exceeded the limit of 1.25–1.30 Mg m^{-3}, above which plant growth can be constrained in fine-textured soil (McQueen and Shepherd, 2002) (Table 4.2 and Fig. 4.4). Under the studied rotations of rice with upland crops bulk density was always <1.2 Mg m^{-3} and penetration resistance was <1.5 MPa at depths greater than 25 cm, indicating that rice roots should likely still grow through this layer without difficulty (Cass, 1999).

It therefore seems very likely that lifted crop productivity in the rice–upland crop rotation primarily stems from improved soil physical conditions and root growth. Rotations of rice with one or two upland crops furthermore increased MacP and SI at 10–20 and 20–30 cm depth, while soil strength was >1.5 MPa at depths greater than 25 cm under R–R–R.

A negative correlation (r = –0.85) between SOC and bulk density, and positive correlation of SOC and SI (r = 0.82) might suggest a relation between SOC storage and a more stable and porous soil structure. However, given the relatively smaller role of soil organic matter as a binding agent in these clay soils, these correlations are probably indirect. Although the upland crops of each rotation were different (maize or/and mung bean), mung bean is a dicot plant with a tap root system while maize is a monocot plant with a fibrous root system (Daniel and Peter, 1995; Grunewald et al., 2007), these systems showed alike soil quality, root growth, yield components and rice yield improvement. This indicates that it is the breaking down of the compacted layer during bed preparation and creation of good aeration conditions that enhance rice yields.

Under R–Mb–R, R–M–R and R–M–Mb there was deeper rooting (Table 4.2) and root biomass (Fig. 4.4) was by a third higher in the 0-10 cm depth, doubled in the 10–20 cm and lifted from absent to 119–134 kg dry matter ha^{-1} in the 20–30 cm depth, relative to R–R–R. The hypothesis that essentially rice-upland crop rotations improve rice yield through improved physical quality of subsoil was directly confirmed through our quantification of root biomass in different depth increments. In general, however, quantifications of root biomass are still scarce due to labor-intensive sampling and root washing. This study clearly demonstrates that a shallow rooting depth is the bottleneck limiting rice productivity in the Mekong Delta and not differences in soil chemical properties, nor water availability. Indeed rice roots generally grow shallow, i.e. not over 0.3 m depth (Jaquie et al., 2012) and rarely exceed 0.4 m depth in continuously flooded fields (IRRI, 1997). In the present field experiment, root biomass was limited below even just 19 cm depth under R–R–R, which probably explains why root proliferation when rotating with upland crops into the 10–20 cm and the 20–30 cm depth increment already had such a pronounced on rice growth and yield. This outcome clearly demonstrates that studying root biomass is key to understand effects of soil tillage management and crop rotation on crop performance in paddy soils. Our recording of root biomass was restricted to the 0–30 cm depth but it seems likely that deeper root growth would have been enabled as well in rice-upland crop rotations, considering the pronounced lowering of soil penetration resistance in the 30–50 cm depth.

In many circumstances it is, however, expected that alleviation of subsoil compaction in paddy soils should have a detrimental effect on rice growth or at least on profit due to higher percolation losses of irrigation water and dissolved nutrients, which require compensation. The irrigation doses were similar in all treatments and even then still higher yields were achieved in rice-upland crop rotations. The combination of clayey soils (66% clay) with inherent low hydraulic conductivity, and an annual high precipitation of 1,500 mm and adequate irrigation water available from the Mekong River kept the plant water supply sufficient. This combination of factors apparently clearly allows for sustainable paddy rice cropping in combination with upland crops. Penetration resistance below 60 cm depth was still greater than 2.5 MPa under all cropping systems and is probably a prerequisite to limit excessive leaching losses. Generation of such a deeper plow pan would not require any extra effort since the subsoil is already sufficiently compacted in the area, where paddy fields are most often several decades old.

Mung bean and maize growth were estimated to hold higher total costs because their cultivation is more labor intensive with raised beds to be prepared and a more demanding harvest as compared with rice. Nonetheless, a greater benefit–cost ratio was achieved with the systems involving maize and mung bean (R–Mb–M, R–M–R and R–Mb–R) because the market price of mung bean and maize is always higher than that of rice, although the prices of these agricultural products can change due to supply-demand relation and inflation. Moreover, crop rotations of rice and upland crops did improve rice yield, with either maize or/and mung bean in rotations having a positive effect. The lowest gross return, net return and benefit–cost ratio was instead estimated for the R–R–R system (Table 4.3). This matches findings based on a rice–upland crop survey conducted in Cho Moi district, An Giang province, by Nguyen and Guong (2010). The similar trends found in that study proof that the findings of this study, though based on data from one year only, are consistent and not greatly affected by market prices that vary over years due to supply–demand relation and inflation. Bastia et al. (2008) and Mandal et al.

(2014) also reported a better net economic return with rice and upland crop rotation systems.

For comparison, the average salary of administrative or technical personnel in the study area is around $2,000 a year. It is 2.3 times higher than the income of farmers from cultivating rice, which amounts to about $875 a year (Table 4.3)). Farmers that are instead growing rice-upland crop rotation systems can receive higher income, which is approximately equal to the average salary of administrative or technical personnel. However, the income from rice or upland crop farming is just a part of the farm households' income. According to the farmer, family members supplement farm incomes by cultivating a fruit garden, animal husbandry or working as handicraftsman at home.

4.5 Conclusions

Our findings provide evidence that including upland crops in rice rotations with temporary beds could correct for the loss in physical quality of soil resulting from long-term intensive rice mono-cultivation, especially at depths of 10–20 and 20–30 cm. These new cropping systems significantly expand the root zone but also enhance soil aggregate stability and soil organic carbon. As a consequence, root growth, rice yield and net return was improved and hence their inclusion in rice-based systems is recommended, at least in the Vietnamese Mekong Delta. Breaking up the existing plow pan by deeper soil preparation in upland crop growing may have detrimental effects in other soil texture/climate combinations e.g. coarse textures or in dry climate may increase water and nutrient leaching, and require further investigation. This study did not yet show the true reason for improved crop growth upon deeper tillage, but it seems evident that plant access to specific (micro)nutrients below the shallow and previously possibly depleted puddle layer is involved. The depth profile and plant uptake of important often depleted nutrients for rice (K, Ni, Cu, Zn and B) should be investigated in long-term field experiments that compare monoculture and rice–upland crop rotations.

Chapter 5

Alleviating soil compaction under rice-upland crop rotations leads to increased nutrient availability and rice yield[#]

[#] This chapter is based on:

Linh, T.B., Sleutel, S., Qui, N.V., Vien, D.M., Khoi, C.M., Guong, V.T., Khoa, L.V., Cornelis, W.M., 2016. Alleviating soil compaction under rice-upland crop rotations leads to increased nutrient availability and rice yield. Soil & Tillage Research. Submitted.

5.1 Introduction

Intensive monoculture-based crop production can cause a decline of soil quality, while its preservation is vital to sustaining and improving long-term agricultural productivity (Karlen et al., 2008; Jill et al., 2011). Indeed, the ultimate result of intensive tillage in every rice crop season is the development of a plow pan closer to the soil surface over time, with reported pans starting at ~ 15 cm depth and extending to 50-60 cm (Chapter 2 and 4). In general, the majority of rice roots penetrate to a depth of about 25 cm in case of unrestricting conditions (Sharma et al., 1994) and so the macro and micro-nutrient availability may be suboptimal when a shallow plow pan is present. This nutrient deficiency would be aggravated by the common cumulative mining of nutrients in Asian rice monoculture, uncompensated by imbalanced fertilizer application.

Deficiency of micronutrients during the last three decades has grown in both magnitude and extent because of increased use of macronutrient inorganic fertilizers, use of high yielding crop varieties and increase in cropping intensity (National Food Security Mission, 2000). Besides macronutrients, micronutrients such as zinc, boron and to a limited extent iron, manganese, copper and molybdenum have also been reported to be deficient. For example, analyses of more than 100,000 soil samples from different agro-ecological zones of India showed 41.7% cases of Zn deficiency and 12% cases of Fe deficiency, whereas deficiency of Mn and Cu was less conspicuous (Singh and Saha, 1995). The reduction of SO_4 to H_2S in flooded soils further limits the availability of Cu and Zn. Indeed, Cu and Zn may form insoluble sulphide (such as CuS, ZnS) under strong reducing conditions, with a phenomenal reduction in the uptake of these nutrients. In another study in different agro-ecological zones all over India, Savithri et al. (1998) showed that Zn doses to correct Zn deficiency varied from 2.5 to 22 kg ha^{-1}; 5.3 kg Zn ha^{-1} proved to be optimum and economical, resulting in a maximum rice yield increase of 4.8 t ha^{-1}.

Our recent research performed on a test paddy field site in the Vietnamese Mekong Delta indicated that soil quality was improved by introducing upland crops in rice cultivation and thus a more diverse crop cultivation pattern (Chapter 2, 3 and 4) and that rice yields were 32-36% higher compared to rice monoculture. Deeper tillage in these rice-upland rotations broke up the existing plow pan and root development was enhanced significantly. Clearly, under such circumstances improvement of soil physical properties has a major impact on rice yields. Since plant water supply is obviously non-limiting in these paddy soils, most evidently nutrient shortages with shallow rooting depth should be considered but the nature of these shortages is unknown. Particularly so because most often information on actual depth distribution of roots is missing. Yet the causal relationship between crop performance and enhanced soil traits in rice-upland crop rotations remains elusive.

In the present study, as a first objective, we compare total (N, S) and plant-available (P, K, Ca, Mg, Fe, Mn, Cu, Zn, B, Ni) levels of nutrients and Si in soil depth intervals that are penetrated by roots under monoculture rice and rice-upland rotations in the field experiment previously presented in Chapter 4. A second objective was to expand (Chapter 4)'s assessment of relationships between soil properties and rice growth, rice yield and evaluate the economic benefit for all three growing seasons after long-term installment of different paddy rice-based cropping systems.

5.2 Materials and methods

5.2.1 Experimental site and treatments

Site description and field experiment was previously presented in Chapter 1 section 1.5.

5.2.2 Soil sampling, field measurements and economic profitability performance

Soil sampling procedure was previously presented in Chapter 2 section 2.2.2.

Field crop measurements were performed as described in Chapter 4 (section 4.2.2).

The economic benefit was calculated as described in Chapter 4 (section 4.2.4) to compare the economic feasibility of the cropping systems during the crop cycle year from 2002 to 2012.

5.2.3 Determination of soil properties

The procedures used for soil physical and chemical analysis and measurements such as soil bulk density, total porosity, macro-porosity, soil penetration resistance, aggregate stability, soil organic carbon, carbon hydrolysable were described in Chapter 2, 3 and 4.

Macro and micro-nutrient elements N, P, K, S, Ca, Mg, Fe, Mn, Si, B, Cu, Ni, Zn were determined for all depth layers. The soils were extracted by NH_4-acetate EDTA at pH 4.65 to estimate plant-available P, K, Ca, Mg, Fe, Mn, Si, B, Cu, Ni, Zn (Cottenie et al., 1982). The extracts were analyzed for their elemental concentrations by a 6300-radial ICP-OES spectrometer (Thermo-Scientific, US). Total N and S was determined by dry combustion elemental analysis with a LECO TruMac CNS (LECO inc., US).

5.2.4 Data analysis

Analysis of variance (ANOVA) was used to compare rice yield and economic profit and soil nutrient stocks between the rotations. Differences amongst individual treatments were determined using Duncan's multiple range test ($P < 0.05$). To test the relationships between the measured plant parameters and soil properties, Pearson's correlation coefficients were calculated for individually sampled soil depths. A discriminant analysis was used to identify those variables that best differentiate between the low and high-yield groups. All analyses were performed using the statistical package SPSS version 20.0 (IBM Corp., 2011).

5.3 Results

5.3.1 Rice production and soil physical quality relationships after 10 years of rotation

There were no significant correlations among measured soil parameters such as BD and PO at 0–10 cm depth and rice yield and rice plant parameters such as rice height, panicle number, rooting depth and root mass density (Fig. 5.1).

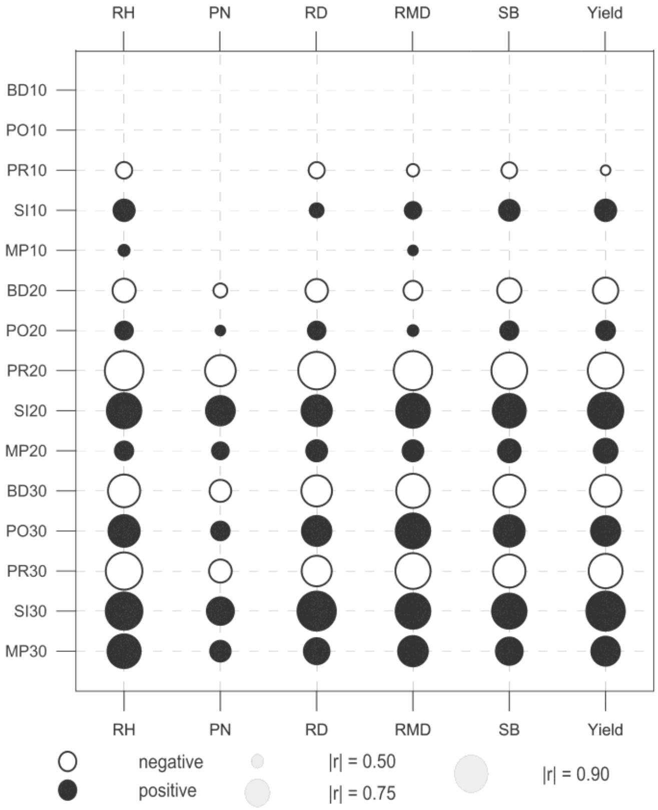


Figure 5. 1 Pearson's correlation coefficients between plant growth parameters and soil physical properties per depth increment (n=16).

BD, bulk density; PO, porosity; PR, penetration resistance; SI, stability index; MP, macro porosity; RH, rice height; PN, panicle number; RD, rooting depth; RMD, root mass density; SB, straw biomass; Yield, grain yield. Suffix 10, 20 and 30 in Y-axis labels denote the 0-10cm, 10-20cm and 20-30cm depths, respectively.

However, PR and SI were strongly negatively and positively, respectively, correlated with almost all plant parameters. In contrast, at depth of 10-20 cm and 20–30 cm, positive correlations ($P < 0.01$, $r > 0.7$) existed with PO, MacP and SI, and negative correlations between BD, and PR and rice yield and plant parameters. The 0-30 cm SOC stock did not relate to any of the plant parameters, while $C_{\text{hydrolysable}}$ showed a strong positive correlation with all ($P < 0.01$) (Table 5.1). In summary, soil with low BD and PR, and high PO, SI, MacP and 0-30 cm $C_{\text{hydrolysable}}$ stocks showed high rice height, panicle number, rooting depth, root mass density, straw biomass and rice yield ($P < 0.01$) (Table 5.1 and Fig. 5.1). Besides, the investigated plant parameters, including root and yield parameters, were all strongly correlated with grain yield and with each other (always $P < 0.01$) (Table 5.1).

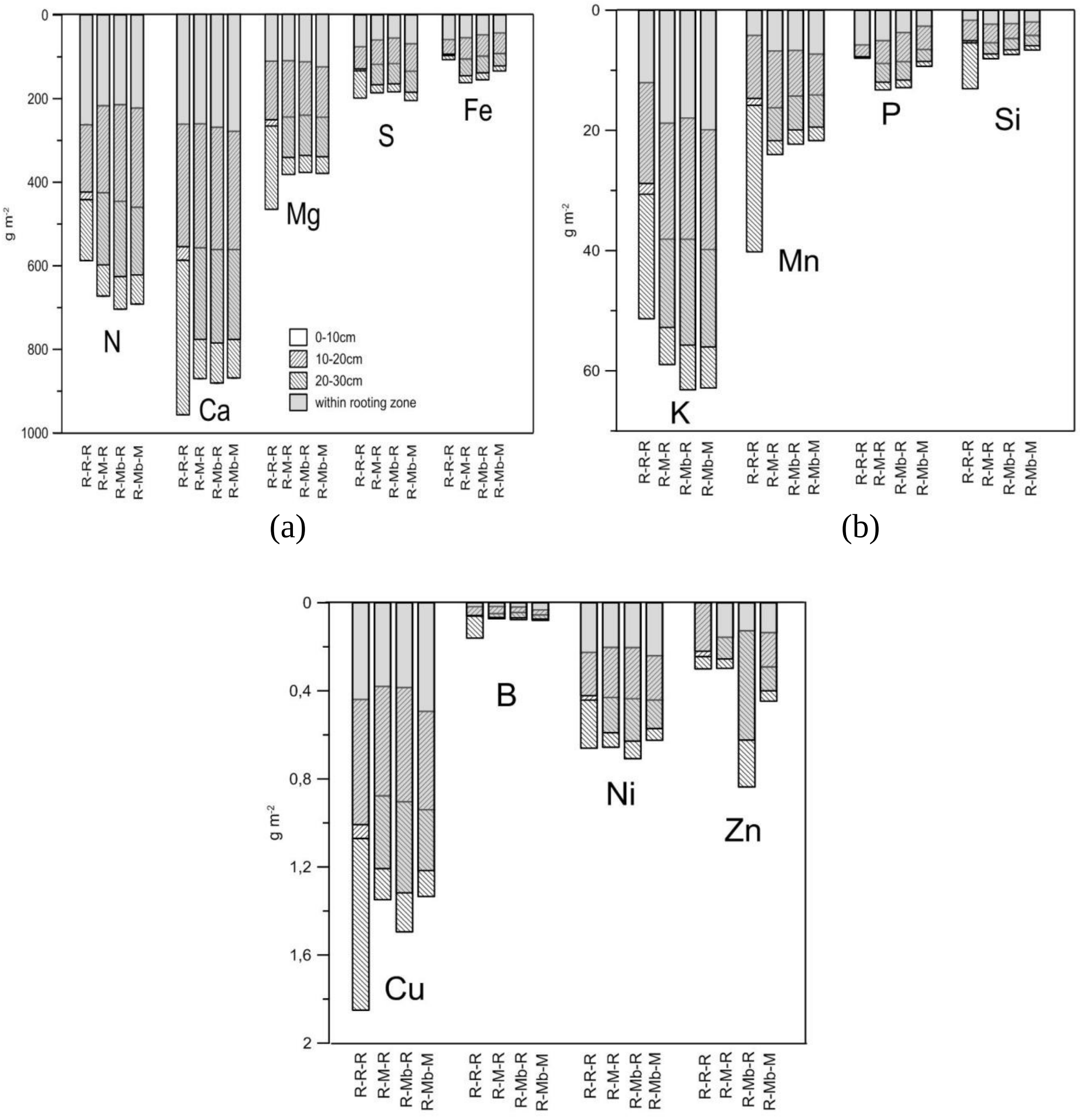
Table 5. 1. Pearson's correlation coefficients (r) between plant growth parameters and soil organic carbon (SOC) and acid-hydrolysable carbon stocks (kg m^{-2}) ($C_{hydrolysable}$) of the 0-30 cm depth layer.

	SOC	$C_{hydrolysable}$	Rice height	Panicle number	Rooting depth	Root mass density	Straw biomass	Grain yield
SOC	1							
$C_{hydrolysable}$	.11	1						
Rice height	.06	$.83^{**}$	1					
Panicle number	.08	$.81^{**}$	$.85^{**}$	1				
Rooting depth	.14	$.86^{**}$	$.93^{**}$	$.90^{**}$	1			
Root mass density	.20	$.89^{**}$	$.95^{**}$	$.84^{**}$	$.94^{**}$	1		
Straw biomass	.03	$.83^{**}$	$.96^{**}$	$.79^{**}$	$.92^{**}$	$.94^{**}$	1	
Grain yield	.15	$.87^{**}$	$.94^{**}$	$.83^{**}$	$.95^{**}$	$.95^{**}$	$.92^{**}$	1

** and ** indicate significant differences at $P < 0.05$ and 0.01, respectively.*

5.3.2 Soil nutrients in the rooting zone

Nutrient stocks of the 0-19 cm root-zone of the intensive rice monoculture system (R-R-R) were always significantly lower than those of the 0-27 cm rice-upland crop rotation systems (R-M-R, R-Mb-R, R-Mb-M) (Fig. 5.2). Rooting zone stocks of all nutrients increase 1.11 to 1.94 times in the R-M-R, R-Mb-M and R-Mb-M systems compared to R-R-R. Particularly the R-Mb-R and R-Mb-M stocks of K and Zn were nearly double compared to R-R-R. The 0-10 cm layer of the R-R-R rotation was most strongly significantly ($P < 0.05$) depleted in K, Zn, Mn, Si, while Ca, Mg, Fe, Cu, B and Ni were at levels comparable to the 10-20 cm layer or 0-10 cm layer of the other rotations (Table 5.2 and 5.3). Soil N and S were significantly ($P < 0.05$) enriched in the R-R-R 0-10 cm layer when compared with R-M-R, R-Mb-R, R-Mb-M (Table 5.2). The 20-30 cm layer of the R-R-R system also had low levels of Fe and P but was relatively enriched in Si and to a lesser extent B compared to the above lying depth increments. Tillage for upland crop soil preparation homogenized nutrient levels in the rice-upland crop rotations with equal distribution of all nutrients over the three sampled depth increments.



(a)

(b)

(c)

Figure 5. 2 Depth distribution of soil nutrient stocks in the 0-30cm depth layer as a function of crop rotation, with indication of the nutrient stock present in the root growing zone per rotation in grey. N, S: total soil stocks; All other elements: presumed plant-available stocks measured in 0.5M NH_4-acetate EDTA at pH 4.65 (n=4). Note different Y-axis ranges for all graphs.

Table 5. 2 Influence of crop rotation on soil macronutrient stocks for three depth increments (means ± standard deviations in g m^{-2}, n=4)

Cropping system	Depth (cm)	N[b]	P	K	Ca	Mg	S
R–R–R[a]	0–10	262.7 ± 6.7 A a	5.8 ± 0.6 A a	12.0 ± 0.4B c	263.0 ± 7.7 c	112.5 ± 2.9 B a	76.5 ± 2.3A
	10–20	179.0 ± 44.0 b	2.1 ± 1.6 b	18.6 ± 1.4 b	325.5 ± 18.4A b	155.1 ± 14.8A b	58.4 ± 8.4
	20–30	145.8 ± 13.7B b	0.1 ± 0.02B c	20.7 ± 0.8 a	369.8 ± 7.6 A a	199.2 ± 9.5 A a	65.1 ± 17.2
R–M–R	0–10	217.1 ± 13.4B	5.1 ± 1.2A	18.7 ± 4.2A	262.3 ± 8.9 c	111.4 ± 3.5B b	60.2 ± 3.7B
	10–20	208.1 ± 43.9	3.8 ± 1.4	19.4 ± 1.4	296.5 ± 10.2AB b	134.7 ± 8.0B a	59.1 ± 9.9
	20–30	247.0 ± 29.7A	4.4 ± 1.0A	20.9 ± 1.9	312.6 ± 20.4B a	137.3 ± 5.2B a	68.0 ± 3.3
R–Mb–R	0–10	214.7 ± 19.4B	3.7 ± 0.3B	17.9 ± 0.6A	270.5 ± 15.7	114.1 ± 5.4 B b	55.5 ± 6.6B
	10–20	230.9 ± 37.9	4.9 ± 3.3	20.2 ± 1.7	292.3 ± 32.7AB	127.7 ± 12.3B ab	62.0 ± 6.9
	20–30	257.7 ± 24.2A	4.3 ± 1.6A	25.1 ± 6.7	319.5 ± 22.7B	136.7 ± 10.0B a	67.6 ± 3.2
R–Mb–M	0–10	222.8 ± 12.6B	2.6 ± 0.9B b	19.8 ± 2.0A	280.3 ± 18.1	125.9 ± 6.6A ab	69.3 ± 8.1A
	10–20	237.2 ± 21.3	3.9 ± 1.5 a	20.0 ± 2.6	282.5 ± 19.0B	120.5 ± 8.5B b	66.3 ± 9.3
	20–30	231.4 ± 30.6A	2.8 ± 1.0A ab	23.0 ± 3.6	307.1 ± 20.9B	134.4 ± 8.7B a	70.3 ± 9.5

[a] *R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.*

[b] *Different uppercase letters in each column denote statistically significant different means between the rotations per depth increment at $P < 0.05$ according to ANOVA and Duncan's multiple range test; Lowercase letters denote significant differences between depth increments within each crop rotation.*

Table 5. 3. Influence of crop rotation on soil micronutrient stocks for three depth increments (means ± standard deviations in g m^{-2}, n=4)

Cropping system	Depth (cm)	Fe[b]	Mn	Si	B	Cu	Ni	Zn
R–R–R[a]	0–10	59.7 ± 2.7A a	4.2 ± 0.5 B c	1.7 ± 0.1C c	0.018 ± 0.001 b	0.44 ± 0.02 c	0.23 ± 0.004AB	-
	10–20	37.6 ± 19.0 b	11.6 ± 2.4A b	3.7 ± 0.5A b	0.043 ± 0.013A b	0.63 ± 0.08A b	0.22 ± 0.04	0.24 ± 0.29
	20–30	9.80 ± 1.7C c	24.4 ± 3.4A a	7.6 ± 1.7A a	0.100 ± 0.025A a	0.78 ± 0.04A a	0.22 ± 0.03B	0.05 ± 0.11 B
R–M–R	0–10	55.4 ± 7.8AB	6.7 ± 0.7 A	2.3 ± 0.2A	0.017 ± 0.003	0.38 ± 0.07	0.20 ± 0.01B	0.16 ± 0.31
	10–20	50.6 ± 12.2	9.5 ± 3.9AB	3.1 ± 1.2AB	0.032 ± 0.016AB	0.50 ± 0.10AB	0.23 ± 0.03	-
	20–30	56.4 ± 8.2A	7.8 ± 0.6B	2.6 ± 0.2B	0.024 ± 0.002B	0.47 ± 0.07C	0.23 ± 0.02B	0.14 ± 0.28B
R–Mb–R	0–10	48.5 ± 3.5BC	6.6 ± 0.4A b	2.2 ± 0.1AB	0.020 ± 0.005 b	0.38 ± 0.07 b	0.20 ± 0.01B b	0.13 ± 0.25 b
	10–20	50.6 ± 11.8	7.6 ± 0.4B ab	2.5 ± 0.3B	0.026 ± 0.005AB ab	0.52 ± 0.08AB a	0.23 ± 0.03 b	-
	20–30	56.1 ± 11.7A	8.0 ± 1.0B a	2.7 ± 0.4B	0.031 ± 0.009B a	0.59 ± 0.04B a	0.27 ± 0.02A a	0.71 ± 0.13A a
R–Mb–M	0–10	44.0 ± 7.9C	7.3 ± 0.6A	2.0 ± 0.3BC b	0.033 ± 0.019	0.49 ± 0.10	0.24 ± 0.03A	0.14 ± 0.27
	10–20	48.9 ± 8.6	6.8 ± 0.9B	2.2 ± 0.1B ab	0.023 ± 0.004B	0.45 ± 0.10B	0.20 ± 0.04	0.16 ± 0.31
	20–30	41.4 ± 9.0B	7.6 ± 0.3B	2.4 ± 0.2B a	0.025 ± 0.003B	0.39 ± 0.08C	0.18 ± 0.03B	0.15 ± 0.18B

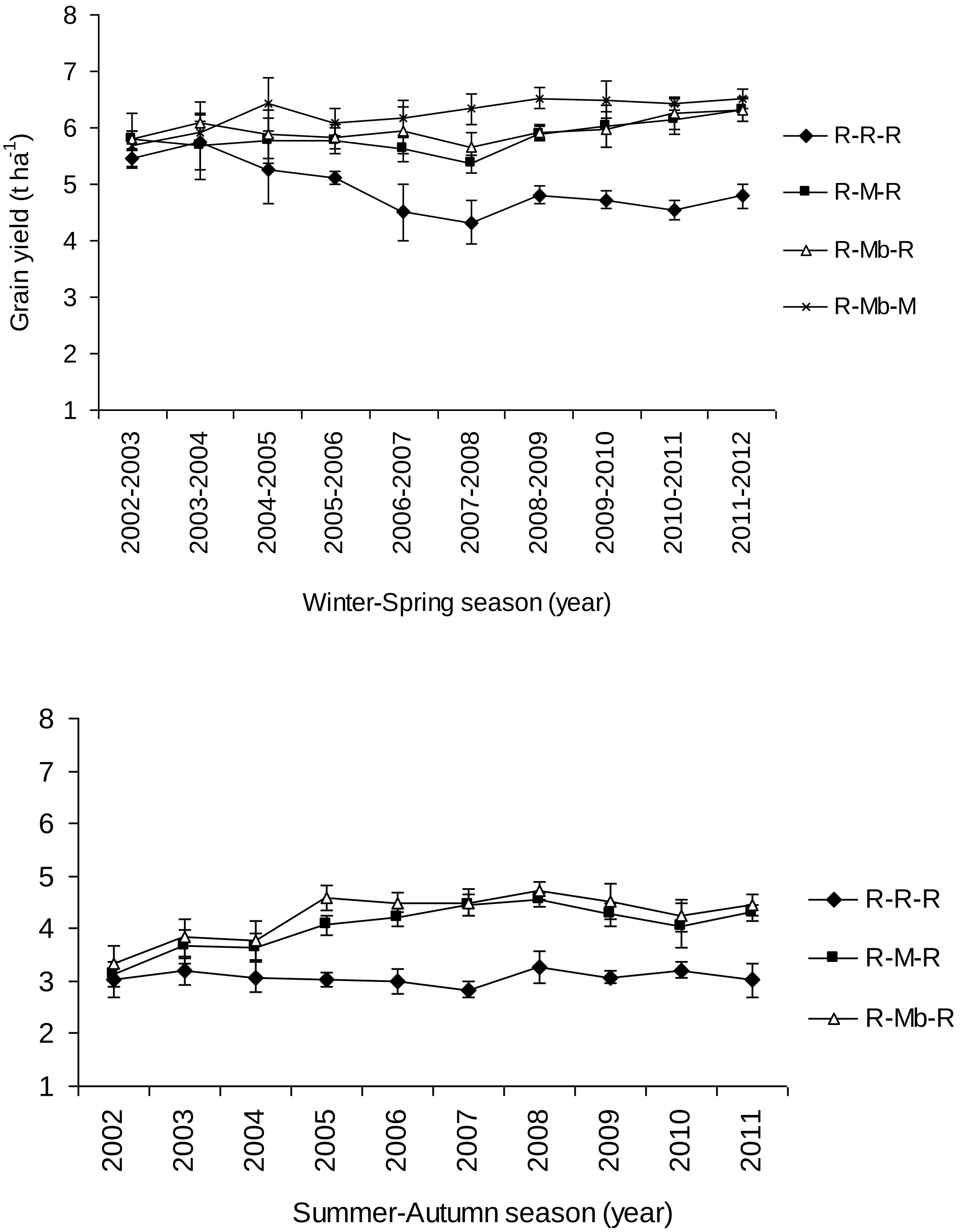
[a] *R-R-R, rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.*

[b] *Different uppercase letters in each column denote statistically significant different means between the rotations per depth increment at $P < 0.05$ according to ANOVA and Duncan's multiple range test; Lowercase letters denote significant differences between depth increments within each crop rotation.*

5.3.3 Effect of crop rotation on rice grain yield and economic profit sequence

The evolution of rice yield per season from 2002 to 2012 is depicted in Fig. 5.3. Substantial long-term improvements in rice yield were observed with inclusion of upland crops in the rotation, although a period of at least three years was required before the difference became significant in both the winter–spring and the summer–autumn season. Over 10 years, the average rice yield recorded in the winter–spring season was 5.8, 6.0 and 6.3 t ha^{-1} for R–M–R, R–Mb–R and R–Mb–M, respectively, and always significantly ($P < 0.05$) higher than the R–R–R yield (4.9 t ha^{-1}). A very similar trend existed for the summer–autumn season with an increase in rice yields for rotations with one upland crop (4.1 and 4.3 t ha^{-1} for R–M–R and R–Mb–R, respectively, vs. 3.1 t ha^{-1} for R–R–R). In case of the R–Mb–M rotation, not rice but maize was cultivated instead in that season. Overall, rice yield in each year and each season was significantly higher ($P < 0.05$) in R–Mb–M, followed by R–M–R and R–Mb–R when compared to R–R–R in all years after three years of rotation.

Rice-upland crop systems also yielded a significantly higher ($P < 0.05$) total profit than intensive rice monoculture (Table 5.4). Over the 10 years trial, rotations of rice with one upland crop (mung bean or maize) had 10-35% lower net return than rice rotated with two upland crops (mung bean and maize). Overall, the yearly income was higher in rice-upland crop rotations, with a similar trend for the 10 years mean income.



(b)

Figure 5. 3 Grain yield of rice for winter–spring season 2002–2003 to 2011–2012 (a) and summer–autumn season 2002–2011 (b), at the experimental site.

R–R–R is rice–rice–rice, R–M–R is rice–maize–rice, R–Mb–R is rice–mungbean–rice, R–Mb–M is rice–mungbean–maize. Bars represent standard deviations for each cropping system (n=4). Note that no data are given for the R-Mb-M in panel (b) since no rice but maize was cultivated in the Summer-Autumn seasons.

Table 5. 4 Long-term evolution in total cost of cultivation, gross return, net return and benefit-cost ratio of different cropping systems (in USD ha^{-1})^{a}

Year	**Cropping system**	**Total cost**	**Gross return**	**Net return**	**B/C ratio**
2002–2003	R–R–R	1,039d	1,302d	264b	1.25c
	R–M–R	1,187c	2,110b	923a	1.78a
	R–Mb–R	1,379b	1,613c	234b	1.17d
	R–Mb–M	1,475a	2,433a	957a	1.65b
2003–2004	R–R–R	1,113d	1,464d	351c	1.32d
	R–M–R	1,279c	2,489b	1,211a	1.95a
	R–Mb–R	1,349b	1,894c	545b	1.40c
	R–Mb–M	1,476a	2,641a	1,164a	1.79b
2004–2005	R–R–R	1,309d	1,745d	436d	1.33d
	R–M–R	1,554b	2,794b	1,240b	1.80b
	R–Mb–R	1,546c	2,456c	910c	1.59c
	R–Mb–M	1,688a	3,189a	1,501a	1.89a
2005–2006	R–R–R	1,686d	1,969d	283d	1.17d
	R–M–R	1,953b	3,474b	1,522b	1.78b
	R–Mb–R	1,827c	2,798c	971c	1.53c
	R–Mb–M	2,010a	3,896a	1,886a	1.94a
2006–2007	R–R–R	1,678d	2,024d	347c	1.21c
	R–M–R	1,992b	3,778b	1,786a	1.90a
	R–Mb–R	1,905c	2,961c	1,056b	1.55b
	R–Mb–M	2,202a	4,016a	1,814a	1.82a
2007–2008	R–R–R	1,909d	2,586d	677d	1.35c
	R–M–R	2,182b	4,663b	2,481b	2.14a
	R–Mb–R	2,106c	3,867c	1,762c	1.84b
	R–Mb–M	2,421a	5,074a	2,652a	2.10a
2008–2009	R–R–R	2,052d	2,737d	685d	1.33c
	R–M–R	2,388b	4,618b	2,229b	1.93a
	R–Mb–R	2,254c	3,910c	1,655c	1.73b
	R–Mb–M	2,611a	5,069a	2,457a	1.94a
2009–2010	R–R–R	2,033d	3,001d	969c	1.48b
	R–M–R	2,346b	5,028b	2,682a	2.14a
	R–Mb–R	2,178c	4,509c	2,330b	2.07a
	R–Mb–M	2,511a	5,397a	2,887a	2.15a
2010–2011	R–R–R	2,074d	2,988d	914d	1.44c
	R–M–R	2,379b	4,801b	2,422b	2.02ab
	R–Mb–R	2,176c	4,297c	2,121c	1.97b
	R–Mb–M	2,520a	5,297a	2,777a	2.10a

2011–2012	R–R–R	2,106d	2,982d	875d	1.42b
	R–M–R	2,464b	4,727b	2,263b	1.92a
	R–Mb–R	2,212c	4,202c	1,990c	1.90a
	R–Mb–M	2,584a	5,159a	2,575a	2.00a
Mean (10 years)	R–R–R	1,700d	2,280d	580d	1.33c
	R–M–R	1,972b	3,848b	1,876b	1.93a
	R–Mb–R	1,893c	3,251c	1,358c	1.68b
	R–Mb–M	2,150a	4,217a	2,067a	1.94a

[a] *Means with a same letter within a column and year are not significantly different at P < 0.05. R─R─R, rice─rice─rice monoculture; R─M─R, rice─maize─rice rotation; R─Mb─R, rice─mung bean─rice rotation; R─Mb─M, rice─mung bean─maize rotation. B/C, benefit─cost ratio (Gross return/ Total cost).*

5.4 Discussion

5.4.1 Multi-year trends in productivity and economic benefit

Considering the long term evolution (10 years) of rice yield, in general, rice crop performed consistently better in all seasons for all rotations with at least one upland crop. The main reason for the difference in rice yield between winter–spring and summer–autumn seasons (Fig. 5.3) may be caused by differences in climatic conditions between two seasons (Dan et al., 2015). Similarly, the slight variations observed within a given season might result from small differences in climatic conditions between years. Rice yield gradually increased after three years of implementing those rotations and reached stable values from later years onwards. On the contrary, under the rice monoculture system, rice yield was stagnant and even declined sometimes.

Likewise, highest economic profit was attained with the systems involving rice-upland crop rotation. This was due to higher rice yield and a better market price of maize and mung bean as compared to rice (Bernhard et al., 2014). Net income was shown to increase significantly with the crop rotation systems compared to rice monoculture, with a similar trend to rice yield. In general, the workload for all cropping systems included land preparation, seeding, sowing fertilizer, spraying pesticides, weeding, irrigation, harvesting, and post harvest operations (storage, transportation). However, labour costs for mung bean and maize were higher as compared with rice because their cultivation is more labour intensive with raised beds to be prepared and a more demanding harvest. On average, the labour input per ha had increased from 65 person days for rice crop season to 95 person days for upland crop season. Nevertheless, the profit over costs (B/C ratio) of rice–upland crop rotation farming systems was higher than that of the traditional mono rice cropping system (Table 5.4). Improvements of rice yield in R–M–R, R–Mb–R and R–Mb–M systems required a period of at least three years of cropping before they became significant. This was probably because after the first three years, soil quality improvement was still at an early stage and thus could not cause a significant difference in rice yield. Here below we discuss potential explanations for improved productivity in rice-upland crop rotations.

5.4.2 Relations between rice yield parameters and soil physical quality

The increases in rice rooting depth and root mass density in upland-rice rotations relative to the R-R-R control were strongly associated with a decrease in BD and PR, and an increase in PO, MacP, SI at 20–30 cm depth and $C_{hydrolysable}$ stocks 0-30 cm (Fig. 5.1 and Table 5.1). These relations could be explained by the at least the partial breaking of the plow pan at depth of 20-30 cm of the deep mixing tillage practice for maize and mung bean cultivation as discussed in Chapter 4.

Rice roots were mostly concentrated in the top 0–10 cm under the rice monoculture system, while, as depicted in Fig. 5.4, rice roots became longer and denser under the newly introduced crop rotation systems. Hence, it was clear that the presence of a shallow plow pan developed by continuous rice monoculture with intensive tillage led to high BD and high penetration resistance which restricted root growth, and thus probably nutrient uptake by the plant (Sharma, 2006). It should also be noted that the positive effects of rice–upland crop rotation on rice root and rice plant parameters, and yield were only discerned at 10–20 and

20–30 cm depth; plant parameters were not correlated with topsoil properties (0–10 cm depth) (Fig. 5.1).

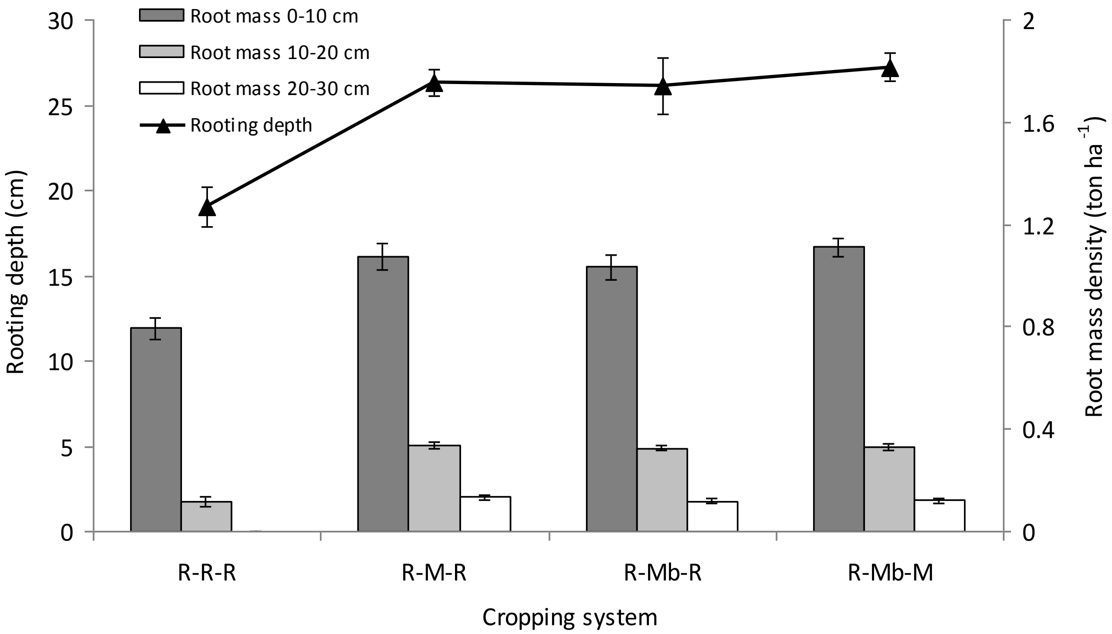


Figure 5. 4 Root distribution under rice crop season for different cropping system.

R–R–R (rice–rice–rice), R–M–R (rice–maize–rice rotation), R–Mb–R (rice–mungbean–rice rotation), R–Mb–M (rice–mungbean–maize rotation). Bars represent standard deviations for each cropping system.

In addition, plant parameters were not correlated with SOC stocks at 0–30 cm depth, while they had great positive correlations ($P < 0.01$) at the same depth with soil organic matter quality expressed in terms of $C_{hydrolysable}$ (Table 5.1). This suggests that rice growth and yield was affected not only by soil compaction as reflected by BD, PO, PR, MacP and SI, but also by soil organic matter decomposition degree (i.e., $C_{hydrolysable}$) but not SOC content. Rice growth and yield both clearly decreased with increasing soil compaction at 20-30 cm, consequently leading to a decrease in continuity of soil pores and reduction in MacP and SI of the plow pan at depth 20–30 cm. Rice yield was also dependent on rice root growth, which was in turn directly associated with changes in soil properties such as BD, PO, PR, MacP, SI and $C_{hydrolysable}$ stocks. With respect to the latter, prolonged inundation has been found to result in accumulation of phenolic lignin residues (Olk et al., 2009b) in paddy fields. A higher degree of chemical degradability of the SOM (i.e. higher proportion of $C_{hydrolysable}$) in the R-Mb-R, R-M-R and R-Mb-M soils on the opposite is caused by prolonged aerated soil conditions during cultivation of the upland crops. Schmidt-Rohr et al. (2004) found that phenolic lignin residues were bound covalently with N in a humic acid fraction. A causal relation between $C_{hydrolysable}$ and plant performance indicators might thus be manifested through concomitant elevated N-release with decomposition of the more labile SOM in the rice-upland rotations and lower binding degree of N to polyphenols. This interpretation is consistent with previous studies of Guong et al. (2010a, b) in the same experimental fields that demonstrated that the rotation of rice with upland crops resulted in significantly greater contents of soil mobile humic acid (MHA), labile organic nitrogen, N mineralization and soil available N supplying capacity compared to intensive rice monoculture systems. In addition, using labeled urea fertilizer (^{15}N) to discriminate soil-N from fertilizer-N taken up by rice showed that there was more soil mineral N taken up in rotation systems compared to rice monoculture system (Guong et al., 2010a, b).

A stepwise discriminant analysis with the 4.5-5.1 t ha^{-1} yield plots vs. the >6 t ha^{-1} plots, furthermore selected $C_{hydrolysable}$ next to PR and SI as non-redundant discriminating variables, with standardized canonical discriminant function loadings of 0.564; -0.679; 0.715. It is, however, just as well possible that these correlations between $C_{hydrolysable}$ and plant performance indicators are indirect, via mutual covariation with soil physical indices.

5.4.3 Plant nutrient depth distributions

The soil nutrient status assessment via NH_4-acetate EDTA extraction and elemental analysis yielded specific insight in potentially plant growth limiting elements. According to Tan et al. (2005), rice exports 14.6 kg N t^{-1}, 2.6 kg P t^{-1} and 2.7 kg K t^{-1}. So on average, triple rice grown in the present experiment removed 185 kg N ha^{-1} yr^{-1}, 33 kg P ha^{-1} yr^{-1}, 34 kg K ha^{-1} yr^{-1}. Given the adequate N and P supply via mineral fertilizer in the established field trial, deficiency of other elements than N and P seems more likely. Levels of Ca, Mg and P were all within ranges recommended by Cottenie et al. (1982) or Fairhurst et al. (2007), also within the 0-10 cm soil layer of the R-R-R rotation. The accumulation of some nutrients such as Ca, Mn, Si, Cu in the subsoil (10-20 and 20-30 cm) of the rice monoculture system can be explained by their limited uptake with shallow rice roots confined to the puddle layer in R-R-R. Cottenie et al. (1982) considered <160 mg K kg^{-1} as low for heavy textured soils and so 0-10 cm K levels in the R-R-R rotation could be considered potentially growth-limiting.

As South Asian farmers at least partly remove rice straw after harvest, a negative K balance is getting prominent, particularly because rice straw is very rich in K (17 kg K t^{-1}; Tan et al., 2005). The same applies to Si, with Si balances often being negative (-150 to -350 kg Si ha^{-1} $crop^{-1}$) in intensive rice systems (Dobermann and Witt, 2000). Indeed, straw was partly removed (about 25%), resulting in an extra 70 kg K ha yr^{-1} and 269 kg Si ha yr^{-1} exported. K was applied at a dose of 30 kg K_2O ha^{-1} $crop^{-1}$ or 72 kg K ha^{-1} yr^{-1}, i.e. just insufficient to compensate grain and straw exports. The 0-10 cm soil layer of the R-R-R rotation contained 129-140 mg K kg^{-1} and at these levels indeed a K-deficiency is possible. Particularly so because Mg levels were very high in all soil layers (1200-1600 mg Mg kg^{-1}) and the resulting very high Mg:K ratio is known to aggravate K-deficiency, even in soils with large K content (Fairhurst et al., 2007). In addition, K fixation may be also prominent given the high clay content with dominance of muscovite (phyllosilicate, mica group) in the study area. Si levels were always below the recommended 40 mg Si kg^{-1} by Fairhurst et al. (2007), extracted in 1M Na-acetate pH 4. The presented Si levels were here determined in 0.5 M NH_4-acetate EDTA pH 4.65, which, however, likely correspond well.

The Ca, Mg, Fe, Mn, Cu and B stock in the 0-19 cm layer, accessed by roots in the R-R-R rotation, was lower of that in the 0-27 cm rooting layer under the rice-upland crop rotations (Fig. 5.2). Although rooting zone stocks of Ca, Mg, Fe, Mn, Cu were at sufficient levels, according to limits set by Cottenie et al. (1982), correlations existed ($P < 0.01$, $r^2 = 0.55$-0.93) between these and rice yield (Table 5.5). Perhaps such relations with rice yield were consequently indirect through mutual correlations with soil physical parameters and rooting zone stocks of other deficient nutrients. Levels of B measured here could not be directly interpreted since the common procedure for B determination is hot water extraction.

Table 5. 5 Pearson's correlation coefficients between rice yield and soil nutrient stocks of the root-zone (n = 16)

	N	P	K	Ca	Mg	S	Fe	Mn	Si	B	Cu	Ni	Zn
Yield	0.91	0.47	0.93	0.95	0.96	0.94	0.74	0.88	0.82	0.77	0.86	0.88	0.32
Significance	*	ns	*	*	*	*	*	*	*	*	*	*	ns

** indicate significant differences at P < 0.01, ns: not significant at the 0.01 level.*

Rice yield of rice-upland crop systems may have been particularly strongly limited by availability of Zn (Table 5.3), next to the above discussed potential Si and K deficiencies. Zn deficiency can reduce cereal yields to drop as much as 50%. Zn was highly deficient in all depth increments over all crop rotations and far below the critical limits of <0.5 mg Zn kg^{-1} (in 0.5 M NH_4-acetate EDTA pH 4.65) set by Cottenie et al. (1982) and 0.6 mg Zn kg^{-1} measured in 1M NH_4-acetate pH 4.8 extracts, proposed by IRRI (2007). Moreover, under anaerobic conditions, Zn availability may be even further lowered because its solubility decreases as pH rises by consumption of protons in reductive processes. With repeated continuous flooding eventually insoluble Zn sulphates and carbonates form. No significant relation could be found between rooting zone extractable Zn stocks and rice yields (Table 5.5), possibly because Zn levels were frequently below the detection limit of ICP-OES analysis of soil extracts. Notwithstanding this, the additional Zn stock supplies due to deeper rooting very likely promoted rice yields in rice-upland crop rotation systems relative to the control R–R–R.

Thus, alleviating soil compaction and cropping system management will make an important contribution to increasing soil nutrition stocks and increasing the rice yield. It should be noted that Zn deficiency is considered the most widespread nutrient disorder in lowland rice (Quijano-Guerta et al., 2002). Indeed, Zn deficiency was realized as plant nutritional problem throughout rice growing countries such as Phillipines, Japan, USA and Brazil (Deb, 1992). At least 70 % of the rice crop is cultivated in flooded conditions resulting in increment in P and bicarbonate concentration which reduces soil Zn availability to the rice crop. According to Cakmak (2008) about 50% of paddy soils are Zn deficient with 35% in Asia only. Improved micronutrient management can help to further increase rice yield potential. Sudhalakshmi et al. (2007) reported that Zn supply in the form of fertilizer increases rice yield.

In the present Vietnamese Mekong Delta field, particularly Zn, K and Si seem to require attention. A remediation recommended by IRRI (2007) is to broadcast 10-25 kg $ZnSO_4.H_2O$ ha^{-1} and blanket 5-10 kg Zn application every 2-8 crops. In the long term Si deficiency is prevented by not removing straw or alternatively by regular application of 1-3 t ha^{-1} calcium silicate (IRRI, 2007). Fertilizer K_2O rates need to take into account both soil stocks as well as straw return rates. At 4-5 t ha^{-1} rice straw remaining in the present field, IRRI (2007) recommends doses of 30 kg fertilizer K_2O per ha for each ton of target grain yield increase over an unfertilized control. The latter is not known for the present experiment, but in the event only K is yield limiting, increasing the R-R-R rotation’s yield up to a par with the rice upland crop rotations would thus require about 50 kg K_2O ha^{-1} $year^{-1}$. Assuming an average price of 1$ per kg of K, such investment would certainly raise net returns. It should also be noted that the uptake of almost all macro and micro nutrients was furthermore likely to be inhibited by high concentrations of Fe in the soil, as demonstrated in a study made by Fageria and Rabelo (1987). Besides K, Zn, Cu, and B supply, Savithri et al. (1998) found that management strategies that improve aerobic conditions enhance rice productivity of soils prone to Fe toxicity by correcting the multi-nutrient deficiency syndrome. At NH_4-acetate EDTA pH 4.65 extracted Fe-levels of 400-700 mg kg^{-1}, Fe toxicity is possible, but requires confirmation. If so, a more efficient way to lift nutrient disorders might be to lower soil solution Fe^{2+} levels due to Fe reduction by adjusting irrigation management to include mid-season drainage or applying Mn^{4+} (via 100–200 kg MnO_2 ha^{-1}), a preferential oxidant to Fe^{3+}.

5.5 Conclusions

Our study showed that there was a close relationship between rice yield and indicators of soil quality. Results reveal that rice–upland crop rotation systems alleviate soil compaction in the subsoil, resulting in improved rice root growth and higher rice yield. The expansion of the rooting zone, which was confined to the 0-19 cm puddle layer under monoculture rice, to a 0-27 cm plow layer under rice-upland rotations makes an important contribution to increasing plant-available soil nutrient stocks. K, Si and Zn are probably deficient and could generally constrain rice growth and yield in Vietnamese Mekong-Delta rice-upland crop systems. Improved micronutrient management can help to further increase rice yield potential and will be required to prevent eventual critical nutrient mining of the expanded 0-27 cm rooting layer.

Rice root growth and yields were not only depending on soil compaction, but also correlated to SOM decomposition level, indicated here from SOM's proneness to acid hydrolysis. There existed a relation with yield, which was probably not causal, but manifested through enhanced available nutrient stocks or by strongly mutual correlation with soil physical traits.

Chapter 6

Temporal variation of hydro-physical properties of paddy clay soil under different rice-based cropping systems[#]

This chapter is based on:

Linh, T.B., Titus, G., Khanh, T.H., Guong, V.T., Khoa, L.V., Cornelis, W.M., 2016. Temporal variation of hydro-physical properties of paddy clay soil under different rice-based cropping systems. Land Degradation & Development. Under revision.

6.1 Introduction

Hydro-physical properties have an impact on the hydrologic cycle and are important factors to assess physical soil quality (Hu et al., 2009; Pulido Moncada et al., 2014a; Castellini et al., 2014). It has long been stated that soil hydraulic properties vary spatially (Nielsen et al., 1973; Strock et al., 2001). Therefore, spatial variability is often considered in water and solute transport modelling studies with an assumption that soil characteristics are constant in time. However, soil properties changes also temporally, displaying variability on a temporal scale. Land preparation, irrigation and tillage, and biological activity could induce such temporal changes, mainly as a consequence of a drastic modification of soil structure (Imeson and Kwaad, 1990; Angulo-Jaramillo et al., 1997).

In comparison with spatial variability, much less studies investigated the effect of temporal variability on soil hydro-physical properties. The main reason for this is that measurements of hydro-physical properties are costly and time consuming, particularly when such measurements are repeated several times within or between seasons (Angulo-Jaramillo et al., 1997). It was only in recent years that temporal changes of hydro-physical soil properties have been the subject of several studies in an attempt to better evaluates the effect of different management systems within a growing season and between seasons or years. Because many soil properties are strongly dependent on soil structure dynamics (Pulido Moncada et al., 2014b), management systems are important agents for changing soil environmental conditions (van Es et al., 1999; Alletto and Coquet, 2009). Cassel (1983) noted that soil parameters such as particle density and particle size distribution usually indicate a small temporal variation because they are more dependent on natural factors, for instance soil formation processes and parent material. Whereas soil parameters such as bulk density (BD), field saturated hydraulic conductivity (K_{fs}) and macro-porosity (MacP) are sensitive to changes in land management, matrix porosity (MatP) does not respond substantially or consistently to changes in cropping systems or tillage practice in upland cropland (Reynolds et al., 2007). Hu et al. (2009) reported that the hydro-physical properties of soils can vary significantly with time and different land uses. Besides, Prieksat et al. (1994) noted that infiltration rates of fine-textured soil increased steadily for chisel plow and did not change for no tillage in a corn field. Ciollaro and Lamaddalena (1998) found that hydraulic properties of a sandy clay increased after plowing and then decrease with time in upland cropland.

On the other hand, short-term changes within a growing season might be substantial as well. For example, hydraulic properties, MacP, total porosity, and BD of the soil can undergo changes due to modifications in the soil surface conditions in strawberry fields (Bamberg et al., 2011). Logsdon et al. (1993) stated that changes in infiltration rates within a season can even be greater than management induced differences. Similarly, Alletto and Coquet (2009) found within-season temporal variability to be more important than tillage and depth effects in upland cropland. A study of Janssen and Lennartz (2007) showed that infiltration rates were strongly depending on the age of the paddy rice field since plow pan seems to develop with rice cultivation history. Lennartz et al. (2009) also reported that the plow pan of old paddy fields is characterized by high bulk density and low saturated hydraulic conductivity as compared to young ones. Beside, studies in paddy rice soils by Zhang et al. (2013), Lin et al. (2014) and Zhao et al. (2015) indicated that alternating drying and wetting following irrigation events modify the soil structure, which is turn influences the infiltration properties.

The common practice of sampling at single times might therefore lead to erroneous conclusions when evaluating the effect of land management practices on hydro-physical soil properties (van Es et al., 1999). As for paddy heavy clay soils, despite the important role of cropping systems with different crop rotations on their hydro-physical properties as presented in previous chapters, their temporal variation has not yet been studied. The objective of this research was therefore to assess the seasonal and inter-seasonal variation of selected hydro-physical properties of a paddy clay soil under four rotation-based cropping systems in the winter-spring season, i.e. the late wet season when rice is cultivated for all treatments, and in the spring-summer season, i.e. the dry season, depending on the treatment when rice is grown or replaced by maize or mung bean.

6.2 Materials and methods

6.2.1 Experimental site and treatments

Site description and field experiment was previously presented in Chapter 1 section 1.5.

6.2.2 Soil sampling and field measurement

Bulk density, macro-porosity, matrix-porosity and field saturated hydraulic conductivity were considered in this study during winter-spring (late wet season) and spring-summer (dry season) of the tenth experiment year. Sampling and measurements were performed three times per cycle, i.e. 15 days after soil preparation (DASP), 45 DASP and 90 DASP (at harvest). The dates at which these operations were conducted during our study period are indicated on Fig. 6.1. Soil sampling procedure was previously presented in Chapter 2 section 2.2.2.

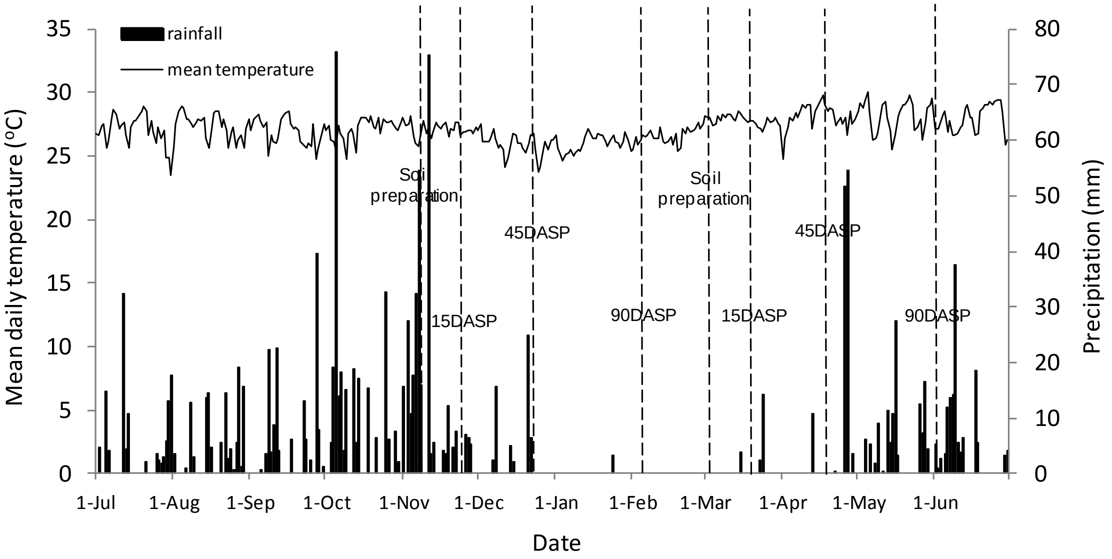


Figure 6. 1 Rainfall and mean temperature at the experimental field during the study period (July 2011 - June 2012). DASP: day after soil preparation.

Infiltration measurements were performed on the field at the soil surface only with a single-ring infiltrometer (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) before a subsequent irrigation event, when the soil of rice plots was moist but not flooded. It had a metal cylinder with a diameter of 28 cm, which was driven firmly into the soil to a depth of about 15 cm, using a driving plate set on top of the infiltrometer. The cylinder was filled with water up to a certain height. At this point water input in the cylinder was stopped and the water level dropped as a result of infiltration into the soil. The height difference of the water level in the cylinder was measured as a function of time for a period of 90 minutes. The infiltration measurement was conducted two times in each of the four replicate plots per treatment.

Quasi-steady state infiltration rate was calculated by differentiating cumulative infiltration I [L] using the equation of Kostiakov (Lal and Van Doren, 1990):

$$I = a \, . \, t^{b} \qquad (1)$$

$$i = \frac{dI}{dt} = a \, . \, b \, . \, t^{b-1} \qquad (2)$$

where t is time of infiltration [T], a *and* b are empirical constants, which are function of the soil's characteristics, i is infiltration rate [L T^{-1}], and assuming quasi-steady state after 5 hours since the beginning of the measurements.

6.2.3 Determination of hydro-physical soil properties

Dry BD was calculated as oven dry soil weight (105°C) of undisturbed soil samples per bulk volume unit using the core method (Grossman and Reinsch, 2002). MacP and MatP parameters define the volume of soil macro-pores and matrix-pores:

$$MacP = \theta_s - MatP \qquad (3)$$

$$MatP = \theta_m \qquad (4)$$

where θ_s ($m^3\ m^{-3}$) is the saturated volumetric water content of the bulk soil. Matric potential values of -1 kPa were used to determine θ_m, as suggested in Reynolds et al. (2007). θ_s and θ_m were determined by sample weight, after having saturated the sample by capillarity and subjected it to a 10 kPa suction on a sandbox (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands), respectively. MacP parameter gives the volume of macro-pores values corresponding to pore diameters greater than 0.3 mm, while soil matrix pores had equivalent diameters ≤ 0.3 mm.

Field saturated hydraulic conductivity (K_{fs}) was calculated from the infiltration data using the equation from Reynolds and Elrick (1990) (Eq. 5).

$$K_{fs} = \frac{i_s}{\dfrac{H}{C_1 d + C_2 r} + \dfrac{1}{\alpha^*(C_1 d + C_2 r)} + 1} \qquad (5)$$

where i_s is steady infiltration rate [L T^{-1}], H is the steady depth of ponded water in the ring [L], d is depth of ring insertion into the soil [L], r is ring radius [L], $C_1 = 0.316\pi$ and $C_2 = 0.184\pi$ are dimensionless quasi-empirical constants that apply for d ≥ 3 cm and H ≥ 5 cm (Reynolds and Elrick, 1990; Youngs et al., 1995). α^* is the soil macroscopic capillary length parameter and represents the relative importance of the gravity and capillarity forces during infiltration (Raats, 1976); $\alpha^* = 0.01$ cm^{-1} was chosen for clayey material and compacted (adapted from Elrick et al., 1989).

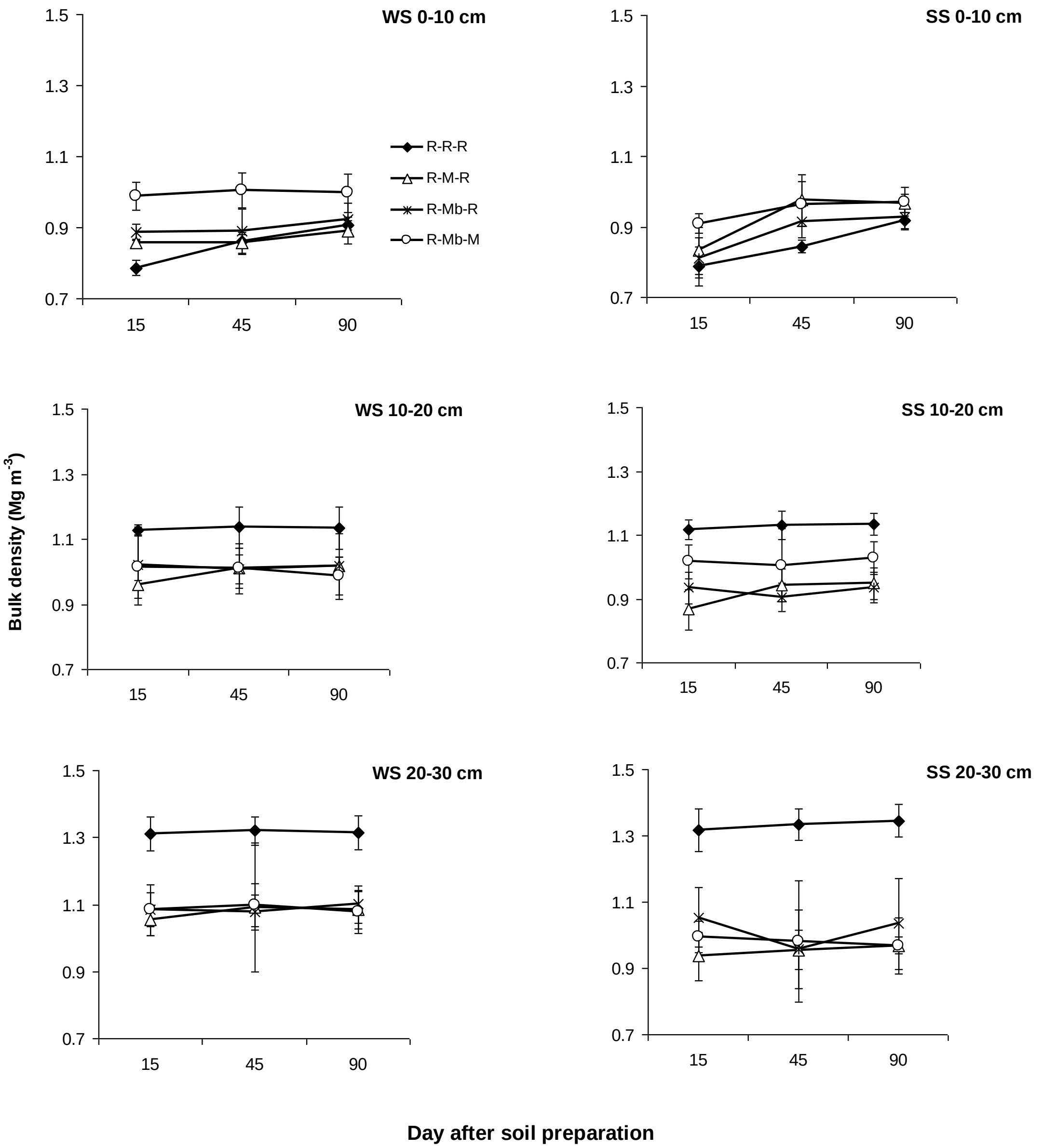
6.2.4 Statistical analyses

A multi-factor analysis (ANOVA) was performed to detect statistical differences and two-way interactions among the seasons, time, treatments and depths. The threshold of significance for the statistical tests was chosen at 0.01. The frequency distribution of K_{fs} data was log-normal, so log-transformed data ($\log_{10} K_{fs}$) were used for the statistical analysis. These analyses were performed using the statistical package SPSS (version 20.0, SPSS Inc., USA).

6.3 Results

6.3.1 Changes in bulk density

Different cropping systems showed BD values at the different times within a range of 0.79-1.34 Mg m^{-3} and 0.77-1.35 Mg m^{-3} for winter-spring (WS) and spring-summer (SS), respectively (Fig. 6.2). Variation can be accounted to the different cropping systems, time (within season), season and depths at which the samples were taken. In the WS season temporal variability in BD was only significant in the top 10 cm for R-R-R (BD showed an increase from 15 DASP to 45 DASP and 90 DASP), whereas no significant change was observed in the other cropping systems. Results for the SS season showed the same absence of temporal variability in the subsoil (20-30 cm). In the top 10 cm, temporal variability could be observed for R-R-R, but also for R-M-R and R-Mb-R. No significant temporal variability was observed for R-Mb-M.



(a) (b)

Figure 6. 2 Change in soil bulk density (Mg m^{-3}) in winter-spring season (WS) (a) and spring-summer (SS) (b) under four different cropping systems at three depths 0-10, 10-20 and 20-30 cm.

Vertical bars represent ± one standard deviation (n=4). R-R-R refers to rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.

Soil BD changed with depth and was affected by the cropping system. Indeed, soil BD of the intensive rice monoculture system R-R-R showed statistical significant increase with depth in both cropping seasons (Fig. 6.2). A numerical increase of BD was also observed for the cropping systems with rotations of rice with upland crops but it was not significant ($P > 0.01$).

Depth and treatment were important factors for the explanation of the observed BD variation, representing 35% and 16% of the variation, respectively and their interaction explained 22% of its variation (Table 6.1). When, because of the large significance of depth, analysing data per depth, treatment and time were the major sources of BD variation at 0-10 cm depth (36% and 21%, respectively), but also their interaction with season was significant (7% and 4%, respectively). At 10-20 and 20-30 cm depth, the major factor was treatment (52-67%), but also season was significant (4-5%) (Table 6.2).

Table 6. 1 Variance components of the bulk density (BD), macro-porosity (MacP), and matrix-porosity (MatP): cropping season (season), time dynamics (time), cropping system type (treatment), depth in the soil (depth) and interactions between these components (combined 0-30 cm depths).

Effect	BD	MacP	MatP
Season	2%	2%	NS
Time	1%	4%	3%
Treatment	16%	37%	19%
Depth	35%	14%	6%
Season*Time	NS[a]	NS	NS
Season*Treatment	NS	NS	NS
Season*Depth	1%	3%	NS
Time*Treatment	NS	NS	NS
Time*Depth	NS	2%	NS
Treatment*Depth	22%	3%	27%

Numbers indicate the percentage in the explanation of the bulk density, macro-porosity and matrix-porosity variance.

[a] *not significant at the 0.01 level.*

Table 6. 2 Variance components of bulk density (BD), macro-porosity (MacP), matrix-porosity (MatP) and field-saturated hydraulic conductivity (K_{fs}): cropping season (season), time dynamics (time), cropping system type (treatment) and interactions between these components.

Effect	BD			MacP			MatP			
Depth (cm)	0-10	10-20	20-30	0-10	10-20	20-30	0-10	10-20	20-30	K_{fs}
Season	NS[a]	4%	5%	13%	NS	NS	NS	NS	NS	38%
Time	21%	NS	NS	19%	NS	NS	13%	NS	NS	15%
Treatment	36%	52%	67%	18%	48%	74%	NS	NS	75%	29%
Season*Time	4%	NS	NS	NS	NS	NS	NS	NS	NS	5%
Season*Treatment	7%	NS	NS	9%	NS	NS	NS	NS	NS	7%
Time*Treatment	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Numbers indicate the percentage in the explanation of the bulk density, macro-porosity and matrix-porosity variance.

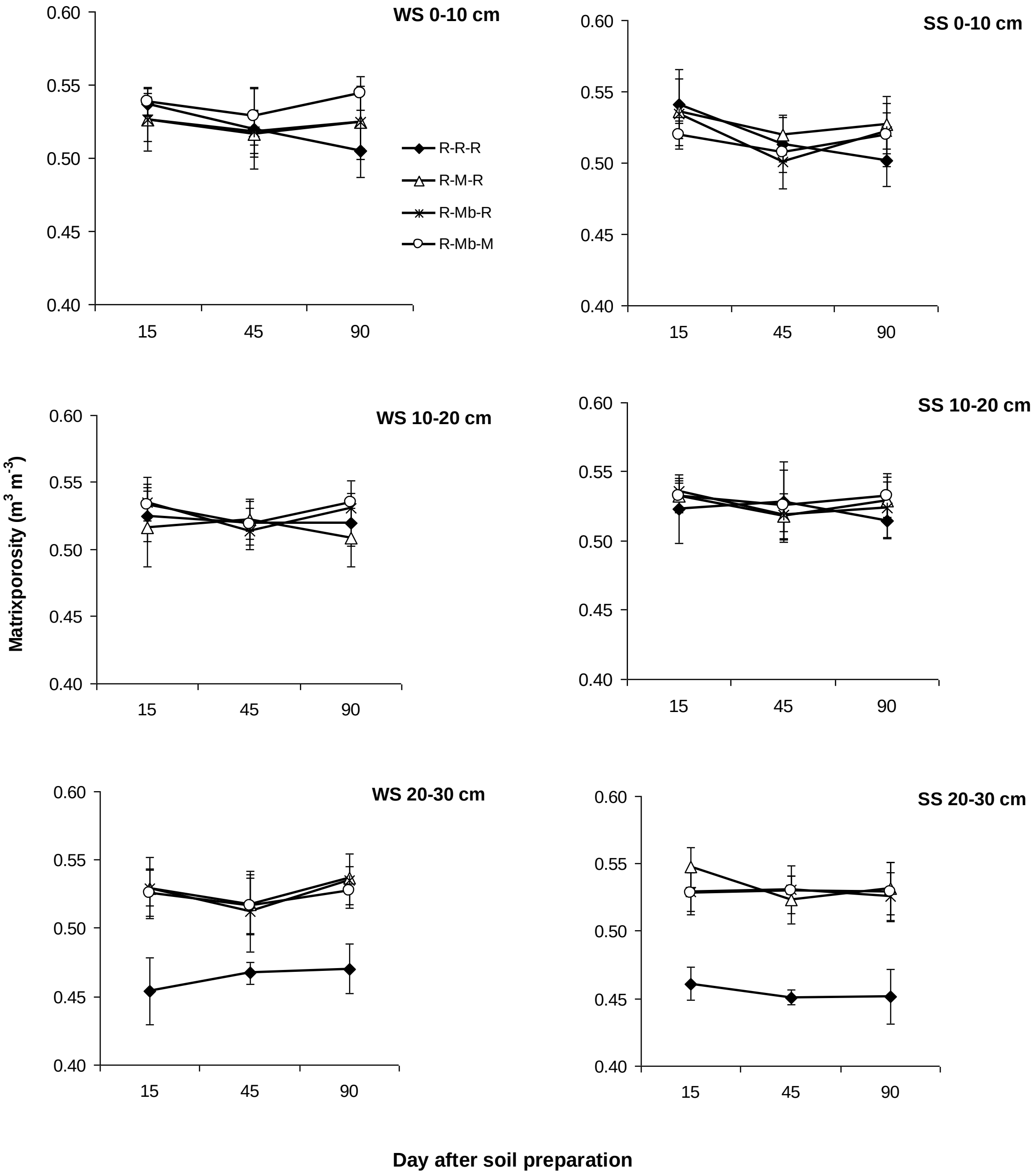
[a] *not significant at the 0.01 level.*

6.3.2 Changes in matrix-porosity (MatP) and macro-porosity (MacP)

MatP values lie within a range of 0.44-0.54 m^3 m^{-3} and 0.44-0.55 m^3 m^{-3} for WS and SS seasons, respectively (Fig. 6.3), which indicates low variation between the two seasons. MacP varied between 0.023 and 0.063 m^3 m^{-3} for WS, and 0.017 and 0.064 m^3 m^{-3} for SS season. The fraction of pores smaller than 0.3 mm (MatP) was about 87-97% of total porosity, indicating a rather low MacP (3-13% of total porosity) (Fig. 6.4).

Intra-seasonal variability was present only for the upper 10 cm, where a declining trend in MatP and MacP with time was evident (Fig. 6.3 and 6.4). Indeed, the difference in MatP and MacP between 15 and 45 DASP, and between 45 and 90 DASP in the upper 10 cm was only significant for R-R-R in both seasons.

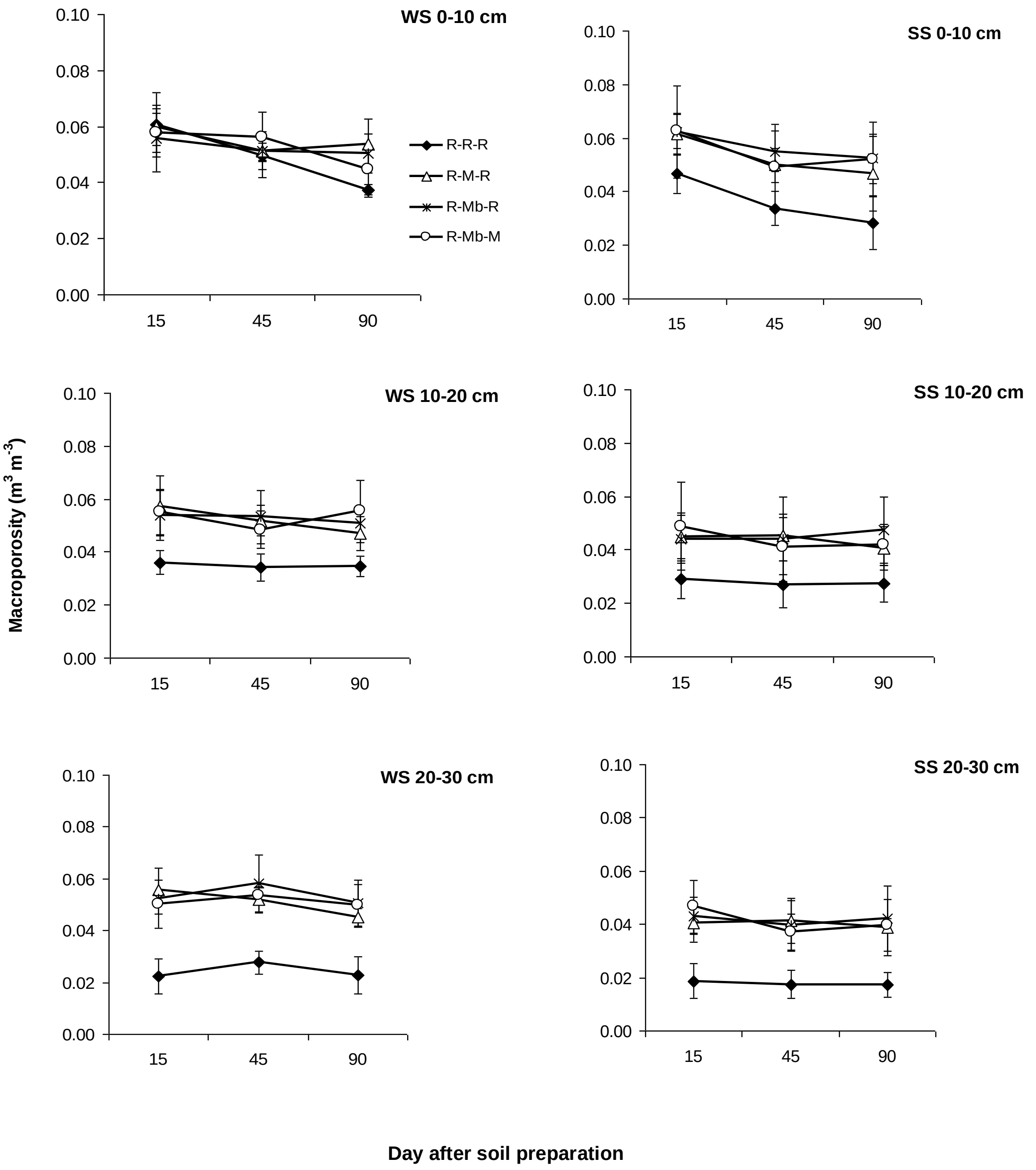
Differences were again lower for intensive rice monoculture treatment as compared to the cropping systems in which rice was rotated with upland crops. Indeed, R-R-R showed values similar to those of the other treatments at 0-10 cm depth; however, they were significantly lower at 10-20 cm and particularly at 20-30 cm depth. These trends were found for both WS and SS (Figs. 6.3 and 6.4).



(a) (b)

Figure 6. 3 Change in soil matrix porosity (m^3 m^{-3}) of winter-spring season (WS) (a) and spring-summer (SS) (b) under four different cropping systems at three depths 0-10, 10-20 and 20-30 cm.

Vertical bars represent ± one standard deviation (n=4). R-R-R refers to rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.



(a) (b)

Figure 6. 4 Change in soil macro porosity (m^3 m^{-3}) of winter-spring season (WS) (a) and spring-summer (SS) (b) under four different cropping systems at three depths 0-10, 10-20 and 20-30 cm.

Vertical bars represent ± one standard deviation (n=4). R-R-R refers to rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.

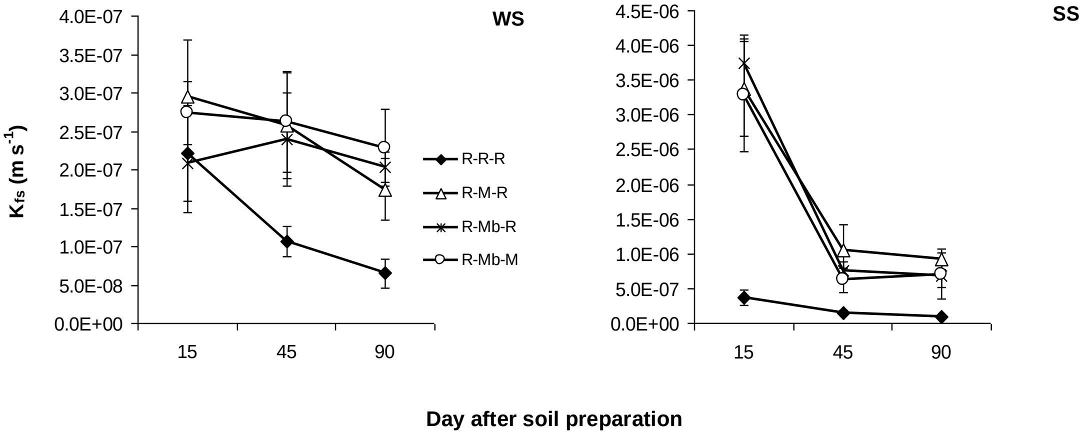
When including all depths in the two-way ANOVA, treatment was the most important factor explaining 37% of the variation in MacP. The second most important source of variation for MacP was depth, explaining 14% of the observed variability, though interactions of season, treatment and time with depth were also significant, explaining 3%, 3% and 2% of the variation in MacP, respectively (Table 6.1). Likewise, MatP was significantly affected by cropping system, depth and their interaction, with the most significant effect being due to treatment and depth interaction, represented by a variance of 27% followed by treatment with 19% and depth with 6%.

When analyzing data per depth, cropping system, time and season factors were the major sources of variation of MacP for 0-10 cm, whereas only treatment showed an effect for 10-20 and 20-30 cm depth (Table 6.2). Regarding MatP, there was a significant difference due to the effect of time and treatment for 0-10 cm and 20-30 cm depths, respectively. Season, time and their interactions did not appear to be significant factors at 10-20 and 20-30 cm depth (Table 6.2).

6.3.3 Changes in field saturated hydraulic conductivity (K_{fs})

Significant differences in K_{fs} (geometric mean) between the two growing seasons were observed (Fig. 6.5) and can be mainly attributed to the treatment with rotations of rice and upland crops. For R-R-R, no significant differences were found between WS and SS at all measurement times. K_{fs} of systems of rice rotated with upland crops in SS at 15 DASP were up to 10 times higher compared to those in WS with values ranging from 4.41×10^{-7} to 4.35×10^{-6} m s^{-1}.

Like BD and MacP, K_{fs} also showed the same trend in variation within the growing season. Indeed, the greatest change in K_{fs} occurred in R-R-R, whereas R-M-R, R-Mb-R and R-Mb-M did not show significant temporal variability in the WS season (Fig. 6.5a). A clear temporal variability was observed for all cropping systems during the SS season, with K_{fs} showing a decrease with time for all treatments. The major decrease occurs between 15 DASP and 45 DASP. The temporal variability effect for K_{fs} during SS was much stronger under maize (R-M-R) and mung bean (R-Mb-R and R-Mb-M) (K_{fs} declined with up to 200%) in comparison with that under rice crop (R-R-R) (K_{fs} declined with up to 100%) (Fig. 6.5b). Beside, the mean values of K_{fs} were significantly higher for systems of rice rotated with upland crops as compared to the rice monoculture for both WS and SS, except 15 DASP in WS.



(a) (b)

Figure 6.5 Change in field saturated hydraulic conductivity (K_{fs}) (m s^{-1}) of winter-spring season (WS) (a) and spring-summer (SS) (b) under four different cropping systems.

Vertical bars represent ± one standard deviation (n=4). R-R-R refers to rice-rice-rice monoculture; R-M-R, rice-maize-rice rotation; R-Mb-R, rice-mung bean-rice rotation; R-Mb-M, rice-mung bean-maize rotation.

Table 6.2 shows the importance of the season factor (38%) for K_{fs}, which was absent for BD and MatP parameters, but which was relevant for MacP at depth 0-10 cm. Also treatment and time greatly affected the variation in K_{fs} (29% and 15%, respectively). Season interaction with time and with treatment was least responsible for differences in K_{fs} (5% and 7%, respectively).

6.4 Discussion

Temporal variability (season and time) was the major cause of variation in BD, MacP and MatP at a depth 0-10 cm only, whereas it was absent deeper in the profile (10-20 and 20-30 cm depths) in both WS and SS seasons (Table 6.2), which can be explained by the plow and puddle layer being present at 0-10 cm depth. This plow layer tended to be structurally fragile with smaller BD values and larger pore space volumes as compared to the soil underneath. This confirms previous reports that plowing changes pore size distribution, creating a loose and fragmented, macro-pore rich soil, which is, however, unstable and will be lost with time (Messing and Jarvis, 1993; Hillel, 1998), and then restoring the soil structure to pre-tillage conditions (Ahuja et al., 1998, 2006; Moret and Arrúe, 2007) due to natural reconsolidation. Zhang et al. (2013) found a similar result in that the low initial of soil BD resulting from soil tillage tended to increase with time as a result of aggregate and particle settlement.

When considering data aggregated over the complete 0-30 cm layer, cropping system type (treatment), depth of soil sampling and interaction between treatment and depth were the important factors for the explanation of the observed variability of BD, MacP and MatP (Table 6.1). The interaction suggests that the effect of the cropping system is systematically most pronounced at a given depth. This was the case at 20-30 cm depth, which reflects the presence of a compacted layer at 20-30 cm depth in R-R-R system and absence of such layer in cropping systems with rotations of rice and upland crops. Indeed, results from Chapter 2 and 4 showed that soil bulk density and soil penetration resistance at 20-30 cm of R-R-R system was clearly higher than that of the puddle layer. This is mainly due to repeated shallow tillage activity three times per year with machinery trafficking for land preparation under wet conditions for rice monoculture for more than 30 years. The soil texture at the field experimental site was clay, so it was vulnerable to soil compaction under wet conditions (above field capacity).

The low (temporal) within-season variation of cropping systems with upland crop rotations compared to intensive rice monoculture system could be explained by aggregates being more stable as reflected by their higher soil aggregate stability index in R-M-R, R-Mb-R and R-Mb-M than R-R-R as reported in Chapter 2 and 4. The aerobic and anaerobic cycles under respectively, the upland crop season (no flooding) and the rice season (flooding) of the rotation system also improved soil structure and hence increased soil macro-porosity as compared to the continuous intensive rice monoculture system where soil was generally submerged. Sacco et al. (2012) also stated that submerging water has effects on macro-pore destruction.

The increase of BD and decrease of MacP and MatP (Fig. 6.2, 6.3 and 6.4) with 0-10 cm depth increment in both WS and SS seasons, especially in R-R-R can be explained by the presence of a compacted layer below the plow layer as discussed earlier. Surely, soils for rice cultivation are puddled in order to make a favorable soil physical condition (Mohanty et al., 2004), and reduce water and nutrient losses through percolation (Greenland, 1985). However, this leads to accelerated soil compaction (Lal, 1985) which might hamper root development of rice and nutrient availability (Chapter 5). The result of intensively tilling the soil every rice crop season in R-R-R is the development of a compact plow pan closer to the soil surface, as reflected in the soil bulk density at 20-30 cm in R-R-R system being always significantly higher than that of all other cropping system at the three measurement times in both WS and SS cropping seasons (Fig. 6.2).

The reverse was observed in cropping systems of rice rotated with upland crops. Explanation of these results requires information of the upland crop cultivation procedures conducted throughout the entire yearly crop rotation cycle. For seedbed construction under cropping systems with upland crops, the preparation of the soil with a tool to invert the surface soil layer caused intensive soil fragmentation and increased pore space between aggregates. This illustrates the advantages of the seedbed planting system (with rotations with at least one upland crop) in breaking the compacted layer during bed preparation and in reducing frequent tillage. Bosscher (2004) already stated that the pore size distribution of the subsoil in paddy puddled soil was very poor and that a large proportion of its porosity was due to residual and storage pores (pore diameter <30 μm). The advantage of this compaction layer is to limit water drainage, thus keeping floodwaters on the rice field (Sharma and De Datta, 1986; Tomar, 1997). However, development of a shallow compacted layer aggravates paddy land degradation and decrease rice yield (Chapter 5).

The significant factors explaining 38%, 29% and 15% of the variation in K_{fs} in soil surface were cropping season, cropping system and time, respectively (Table 6.2). Probably, these changes reflect a change in soil MacP that directly influenced K_{fs}. We found a significant correlation ($P < 0.01$) with $r^2 = 0.58$ between MacP and K_{fs}. These findings support those of previous studies that noticed relation of macro-pore volume with hydraulic conductivity (Alletto et al., 2010; Sacco et al., 2012). The decline in K_{fs} from an early stage of the cropping season (15 DASP) towards mid and end of season (45 and 90 DASP) could be associated with the loosening effect of recent tillage for rice or seedbed preparation by shovel hoe for maize and mung bean cultivation. This reduction is the result of soil consolidation processes (Mapa et al., 1986), and sealing formation and settlement of tilled soil under irrigation events significantly reducing the macro-porosity and hydraulic conductivity at 45 and 90 DASP. Such changes were also reported by Kukal and Aggarwal (2002), Cameira et al. (2003), Pare et al. (2011) and Sacco et al. (2012).

The difference in K_{fs} between WS and SS season for the rotation with rice and upland crops systems could be a consequence of the difference in cultivated crop and thus the difference in soil preparation of the field. For these cropping systems, rice was cultivated on flat fields in the WS season, whilst in the SS season, the upland crops were cultivated on soil beds which were prepared with hoe that broke the compacted subsoil during their preparation. This resulted in the topsoil being very loose after soil preparation. The treatment with rice monoculture showed similar values at the same measurement times of both seasons. The similarity of this system may be due to its common cultivation history of paddy field. Continuous cultivation of lowland puddled rice year after year results in the development of hard subsurface layers. Therefore, the partly removal of the plow pan from the paddy may effectively increase K_{fs} in cropping systems with rice and upland crops. However, this might have a detrimental effect on nutrient losses due to higher percolation of irrigation water in paddy soils. It should be noted that the farmers do not have to pay the cost for irrigation water. The cost of irrigation comprises actually the cost of fuel or electricity for pumping. It is around 5% of the total cost in the dry season while this cost is less than 1% in the rainy season.

Our findings suggest that temporal variability with respect to hydraulic conductivity was present and should be considered. This matches findings based on time effects on hydraulic conductivity that have also been observed by other researches and various factors to explain the temporal changes that were identified. These factors mainly consisted of management practices (Somaratne and Smettem, 1993; Logsdon and Jaynes, 1996; Alakukku, 1996), soil consolidation or settlement (Moret and Arrúe, 2007; Petersen et al., 2008), biological activity (Das Gupta et al., 2006; Petersen et al., 2008), rainfall (Somaratne and Smettem, 1993; Das Gupta et al., 2006) and wetting-drying cycles (Petersen et al., 2008; Sacco et al., 2012, Zhao et al., 2015).

6.5 Conclusion

Temporal effects appeared to be one of the main sources of variability of bulk density and macro-porosity at the topsoil (0-10 cm), beside the cropping system factor. In the subsoil (10-20 and 20-30 cm), the cropping system was found to have the strongest effect on these soil properties. Temporal change of bulk density, matrix-porosity and macro-porosity within season and between seasons was limited for cropping systems with upland crop rotations, whereas it was clearly present for the rice monoculture system. Rotating rice with two upland crops did not result in different temporal variation of physical soil properties compared to a rotation with only one upland crop, but differences with rice monoculture were substantial. This can be assigned to soil aggregates being more stable due to the alternation of flooding-drying and the reduction in puddling operations under rice-upland crop rotation systems as compared to the intensive continuous rice monoculture system where soil was generally submerged and subjected to intensive shallow tillage and puddling. Like cropping season and cropping system, time of soil sampling was found to have effects on field saturated hydraulic conductivity of the topsoil which was well related to macro-porosity. Results indicate that the soil sampling depth with 10 cm depth increments down in the soil profile of paddy clay soil should be accounted for when evaluating the effect of rice-based cropping systems with rotations with upland crops on physical soil quality.

Chapter 7

Effects of cropping system on soil properties of paddy clay soils in small-scale farmers' fields[#]

This chapter is based on:

Linh, T.B., Tran, V.T.T., Guong, V.T., Khoa, L.V., Olk, D.C, Cornelis, W.M., 2016. Effect of contrasting tillage on properties of a Vietnam clay soil under rice-based cropping rotations. Soil Research. Accepted.

7.1. Introduction

Continued cultivation of rice leads to declining soil fertility (Dwivedi et al., 2001; Guong et al., 2010) as well as soil productivity (Mandal et al., 2014). Rice fields in the Mekong Delta are also subjected in each rice season to conventional puddling with repeated plowing and field leveling to reduce water loss through percolation and to help in weed control (Farooq et al., 2011). However, long term rice monoculture with puddling to the same shallow depth may result in the establishment of a compacted zone just below the plowed layer.

Many agricultural practices are known to influence soil properties. These include crop type (Scott et al., 1994), cultivation methods (Gantzer and Blake, 1978), and application of organic residues (Anderson et al., 1990; Ekwue, 1990). Effects of cropping systems on soil physical properties are often related to changes in soil organic matter (Ghidey and Alberts, 1997; Haynes, 2000). Studying the effects of cropping systems and management practices on soil properties provides essential information for assessing their sustainability and environmental impact (Ishaq and Lal, 2002).

Controlled field experiments in the Mekong Delta showed that rice monocultures resulted in physical and chemical deterioration of soils thus rendering them less productive, whereas rotating rice with upland crops resulted in substantial improvements (Chapter 2, 3, 4, 5 and 6). During experiment period, we organized a field demonstration for local farmers to raise farmer awareness about new farming practices. Based on the demonstration and subsequent discussion with farmers, some farmers then choose to realize new cropping system on their farm. As a result of this activity, rice monoculture fields in the study area are gradually rotated by farmers with upland crop. Particularly, some farmers who have small farm size like to replace traditional rice monoculture by upland crop monoculture. The objective of this study was to evaluate the effects of different cropping systems ranging from rice monoculture, rice-upland crop rotation to upland crop monocultures on the physical and chemical quality of alluvial heavy clay soils in small-scale farmers' fields in the Mekong Delta. This work was performed in collaboration with 40 farmers who shifted from rice monocultures to the newly introduced cropping systems in which at least one upland crop is grown per year. This chapter differs from previous chapters in that (i) additional cropping systems (upland crop monoculture) were tested and (ii) uncontrolled farmers' fields spread over the region of interest were selected for soil sampling rather than plots from one controlled experiment.

7.2 Materials and methods

7.2.1 Study area and soil sampling

Study area description and soil sampling procedure was previously presented in Chapter 1 section 1.5.

7.2.2 Soil physical and chemical analysis

The procedures used for soil physical and chemical analysis such as soil texture, soil bulk density, particle density, total porosity, plant available water capacity, macroporosity, aggregate stability, soil penetration resistance, pH, EC, CEC, soil organic carbon, carbon hydrolysable were described in Chapter 2 and Chapter 3.

7.2.3 Statistical analyses

Analysis of variance was conducted on all the soil properties following a randomized complete design (Gomez and Gomez, 1984) in order to compare differences among cropping systems and among depths using SPSS 20.0 software. When cropping system or soil depth effects occurred, significant differences were determined using the Duncan's multiple range test (DMRT) at 5% probability. Standard deviations are given to indicate the variation of a set of data values. In addition, linear correlation analyses were conducted to identify relationships between soil BD, SP and SOC.

7.3 Results

Soil texture of all depths in all cropping systems was classified as clay, with mean sand content ranging from 15 to 25 g kg^{-1}, silt content from 291 to 318 g kg^{-1}, and clay content from 656 to 692 g kg^{-1} (Table 7.1). There were no significant differences in sand, silt and clay content among the cropping systems at three different depths (0-10, 10-20 and 20-30 cm) nor among depths within each cropping system.

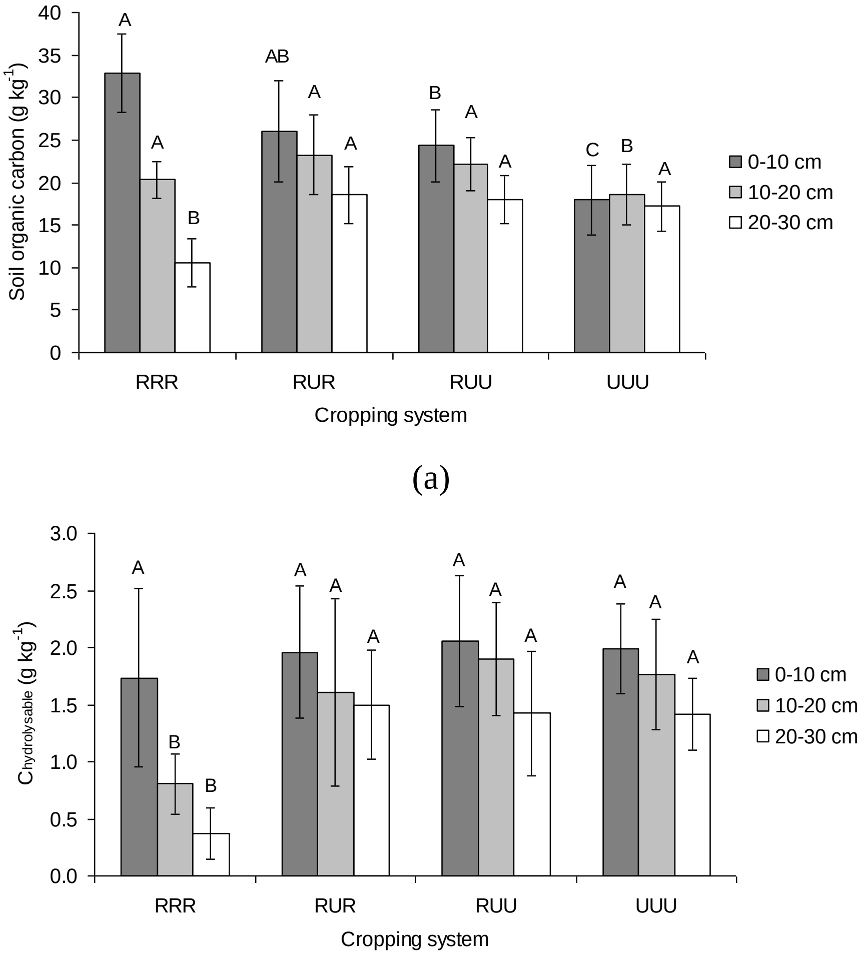
Table 7.1 Particle size distribution for four cropping systems at three soil depths[1]

Cropping system	Depth (cm)	Sand 50–2000µm	Silt 2–50µm	Clay <2µm
			(g kg^{-1})	
RRR	0-10	22.8 ± 11.2	310.1 ± 38.1	668.1 ± 39.9
	10-20	19.2 ± 7.2	308.8 ± 31.6	672.0 ± 34.3
	20-30	13.6 ± 4.4	299.7 ± 35.6	686.7 ± 37.0
RUR	0-10	15.0 ± 7.0	301.8 ± 38.0	683.2 ± 33.1
	10-20	21.2 ± 13.2	303.9 ± 33.6	674.9 ± 34.4
	20-30	16.4 ± 8.4	309.0 ± 20.3	674.6 ± 24.1
RUU	0-10	25.3 ± 11.3	318.2 ± 48.3	656.5 ± 47.8
	10-20	23.2 ± 7.4	313.3 ± 37.3	663.5 ± 37.3
	20-30	21.0 ± 6.4	307.4 ± 34.0	671.5 ± 34.7
UUU	0-10	19.8 ± 8.2	311.5 ± 44.0	668.8 ± 47.0
	10-20	18.8 ± 7.3	308.0 ± 39.0	673.2 ± 42.2
	20-30	15.9 ± 6.3	291.4 ± 28.5	692.8 ± 28.1

[1] *RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.*
Using DMRT no parameter differed significantly (P > 0.05) among cropping systems at any depth or among the depths within any cropping system. Numbers follow ± symbol represent the standard deviations.

Soil pH and CEC were not significantly different among cropping systems or depths (Table 7.2), in contrast with EC which at the 0-10 cm depth was significantly lower for UUU than for RUR. However, there were no significant EC differences at the 10-20 and 20-30 cm depths among cropping systems as well as among depths within each cropping system.

Cropping systems significantly affected SOC content (g kg^{-1}) as well as SOC stock (Mg ha^{-1}), with the highest values found at 0-10 cm depth and values further decreasing with depth in all the cropping systems, except UUU (Fig. 7.1 and 7.2).



(a)

(b)

Figure 7. 1 Influence of cropping system on soil organic carbon (a) and HCl hydrolysable carbon ($C_{hydrolysable}$) content (b) in three depth intervals.

RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.
Different letters in each column within depth layer denote statistically significant differences ($P < 0.05$) among the cropping systems.

The SOC content in RRR in the top 10 cm (33 g kg^{-1}) was significantly greater than in the top horizon of RUR, RUU and UUU (26, 24 and 18 g kg^{-1}, respectively) ($P < 0.05$). In contrast, at 20-30 cm, the highest SOC contents ranged from 17 to 19 g kg^{-1} for UUU, RUU, and RUR, and RRR had the lowest SOC (10 g kg^{-1}). Numeric trends in SOC stocks followed those of SOC concentrations (Fig. 7.2). Considering the total 0-30 cm profile, the mean value of total SOC stocks per hectare was greatest in RUR (72.3 t ha^{-1}), followed by RUU (68.3 t ha^{-1}), RRR (66.42 t ha^{-1}) and UUU (59.31 t ha^{-1}) and was significantly greater for RUR, RUU and RRR than for UUU. However, differences in SOC stocks were not significant among RRR, RUR and RUU.

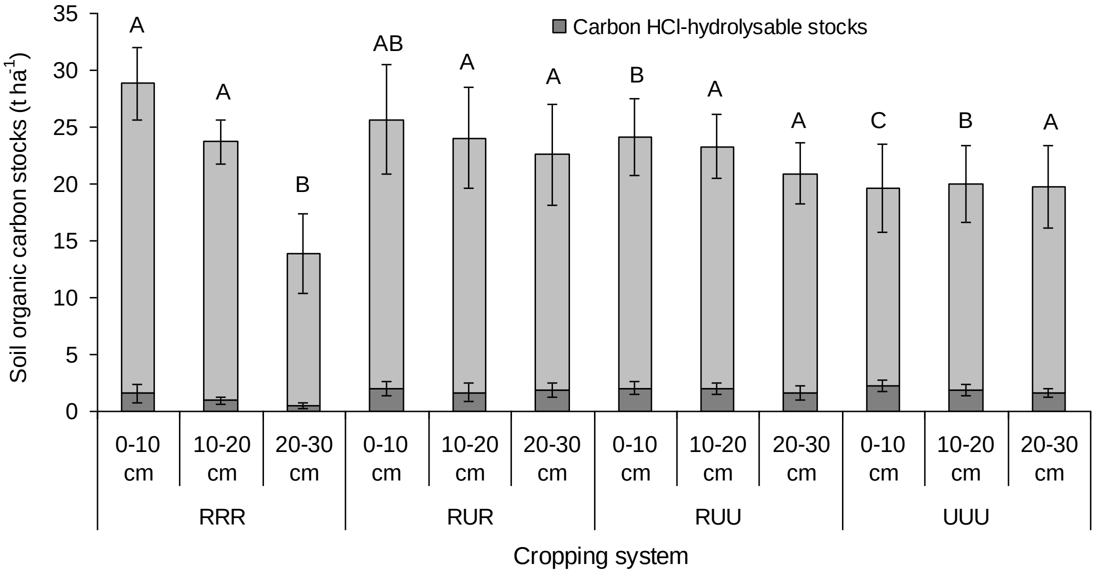


Figure 7. 2 Influence of cropping system on soil organic carbon stocks and HCl-hydrolysable soil C stocks at 0-10, 10-20 and 20-30 cm depths.

RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation. Bars represent standard deviations for each soil depth of each cropping system.

Different letters in each column within depth layer denote statistically significant differences ($P < 0.05$) among the cropping systems.

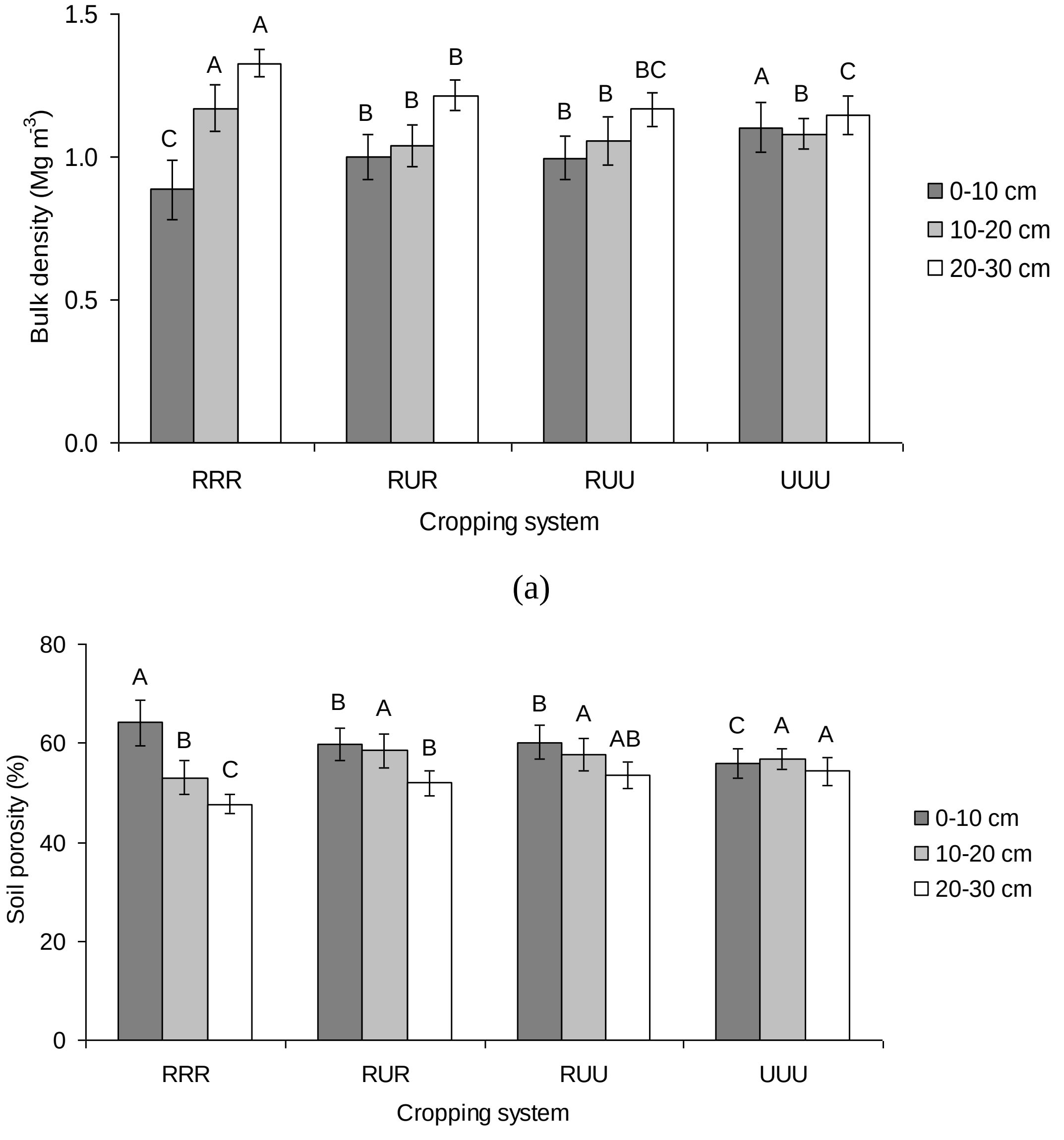
Replacement of long-term RRR with RUR, RUU or UUU caused a significant increase in $C_{hydrolysable}$ at the 10-20 and 20-30 cm depths (Fig. 7.1b). At 10-20 and 20-30 cm $C_{hydrolysable}$ under RUR, RUU and UUU were two and three times greater, respectively, than with RRR. A similar trend existed with total $C_{hydrolysable}$ stocks per hectare at the 10-20 and 20-30 cm depth (Fig. 7.2).

Despite differences in SOC content between cropping systems and depths, significant cropping system effects on particle density (PD) were not observed among depths within each cropping system or among cropping systems at each depth of 0-10 cm, 10-20 cm, and 20-30 cm (Table 7.2). Bulk density (BD) values on the other hand were significantly different between RUR, RUU and UUU, and RRR at all depths (Fig. 7.3a). Indeed, BD at 0-10 cm depth was significantly less for RRR than for the rice-upland crop rotation systems (RUR and RUU) and upland crop monoculture (UUU). However, at the 10-20 cm and 20-30 cm depths, BD was significantly greater for RRR than for all other cropping systems. Within each cropping system, BD increased numerically with soil depth except for UUU. The significant differences in soil porosity (SP) among the depths or among the cropping systems (Fig. 7.3b) are a direct result of the bulk density differences. An increase in soil strength (Fig. 7.4) was also associated with the reduction in soil porosity and increase in soil bulk density with increasing depth and among cropping systems. Soil penetration resistance (PR) increased numerically with depth for all cropping systems, while it had a wider range of values for RRR than for the other cropping systems (Fig. 7.4). Below 15 cm, RRR had numerically greater penetration resistance than did the other cropping systems.

For the topsoil, PAWC did not differ significantly among cropping systems (Table 7.2). At the 10-20 cm depth, UUU had a significantly lower PAWC than did RUR and RUU. For the 20-30 cm depth, RRR had significantly lower PAWC (20-32% lower) than did all other cropping systems.

The MacP was significantly affected by both cropping system and depth, decreasing numerically from 0-20 cm to 20-30 cm for all cropping systems (Table 7.2). Rice monoculture (RRR) and the rice-upland crop rotations (RUR and RUU) had similar MacP values at 0-10 cm, which were significantly lower than that of the UUU system. The rice monoculture system had a significantly lower MacP for

10-20 cm and 20-30 cm (26-37% and 33-40%, respectively) than did the rice-upland crop rotation systems and upland crop monoculture.



(a)

(b)

Figure 7. 3 Influence of cropping system on soil bulk density (a) and soil porosity (b) in three depth intervals.

RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.

Different letters within each depth layer denote statistically significant differences (P < 0.05) among the cropping systems.

The use of upland crops in the rotations showed a significant improvement in SI compared to rice monoculture at the 20-30 cm depth (Table 7.2). Comparison of overall SI in the top 30 cm reveals that UUU had the highest SI followed by RUU, RUR and RRR (Table 7.3).

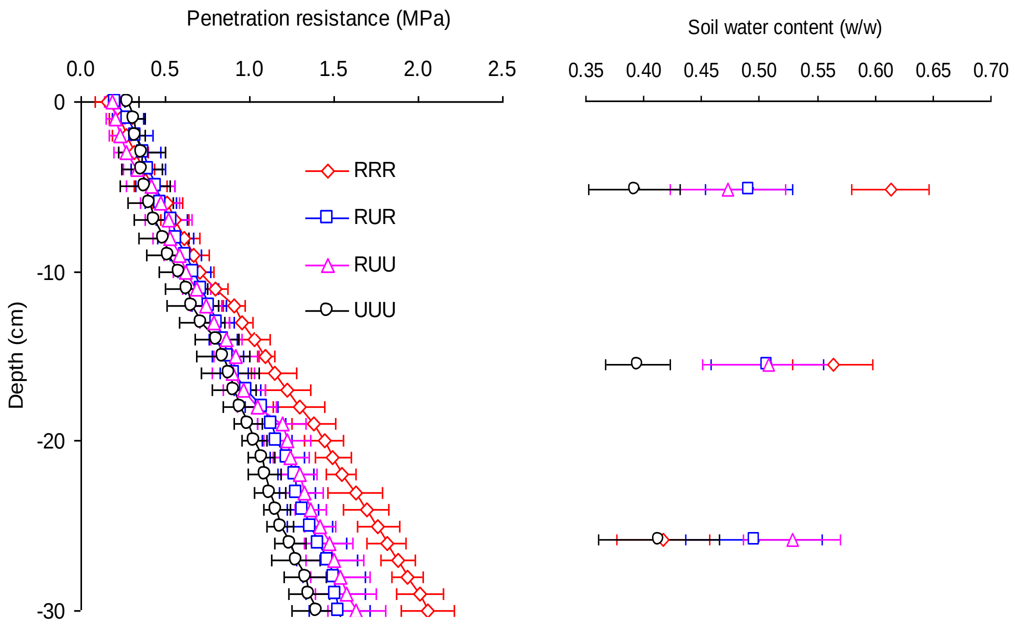


Figure 7. 4 Soil strength and corresponding soil water content for the 0-30 cm depth (n=10) in rice-rice-rice (RRR), rice-upland crop-rice rotation (RUR), rice-upland crop-upland crop rotation (RUU), and upland crop-upland crop-upland crop (UUU). Bars represent standard deviations for each cropping system.

Table 7. 2 ***Influence of crop rotations on selected soil chemical and physical quality indicators and parameters[1].***

Cropping system	Depth (cm)	pH (-)	EC (µS cm^{-1})	CEC (cmol+ kg^{-1})	PD (Mg m^{-3})	PAWC (m^{3} m^{-3})	MacP (m^{3} m^{-3})	SI (-)
RRR	0-10	5.41 ± 0.32	616 ± 179 AB	24.4 ± 3.0	2.47 ± 0.07	0.250 ± 0.033 a	0.0437 ± 0.0076 B a	1.52 ± 0.27 B a
	10-20	5.38 ± 0.21	622 ± 151	24.4 ± 3.1	2.50 ± 0.05	0.241 ± 0.024 AB a	0.0389 ± 0.0088 B a	1.28 ± 0.20 B b
	20-30	5.52 ± 0.20	633 ± 139	24.5 ± 3.0	2.54 ± 0.02	0.178 ± 0.022 C b	0.0281 ± 0.0055 C b	0.85 ± 0.12 D c
RUR	0-10	5.46 ± 0.28	643 ± 123 A	24.0 ± 1.0	2.49 ± 0.06	0.254 ± 0.042 a	0.0490 ± 0.0141 B ab	1.54 ± 0.31 B a
	10-20	5.50 ± 0.25	618 ± 158	23.5 ± 1.5	2.51 ± 0.05	0.261 ± 0.020 A a	0.0524 ± 0.0073 A a	1.35 ± 0.28 B ab
	20-30	5.53 ± 0.23	610 ± 129	23.0 ± 1.2	2.53 ± 0.04	0.222 ± 0.032 B b	0.0417 ± 0.0082 B b	1.19 ± 0.18 C b
RUU	0-10	5.49 ± 0.27	517 ± 125 AB	24.8 ± 3.7	2.51 ± 0.04	0.253 ± 0.035	0.0537 ± 0.0127 AB a	1.82 ± 0.30 B a
	10-20	5.58 ± 0.24	531 ± 196	24.3 ± 4.2	2.50 ± 0.02	0.256 ± 0.023 A	0.0543 ± 0.0109 A a	1.36 ± 0.25 B b
	20-30	5.59 ± 0.25	575 ± 143	24.2 ± 3.2	2.51 ± 0.03	0.261 ± 0.041 A	0.0435 ± 0.0083 AB b	1.44 ± 0.29 B b
UUU	0-10	5.56 ± 0.24	491 ± 144 B	23.9 ± 3.0	2.50 ± 0.04	0.231 ± 0.031	0.0622 ± 0.0104 A a	2.18 ± 0.51 A a
	10-20	5.51 ± 0.25	512 ± 187	23.8 ± 2.8	2.49 ± 0.03	0.226 ± 0.025 B	0.0612 ± 0.0132 A a	2.05 ± 0.35 A ab
	20-30	5.65 ± 0.19	507 ± 157	24.2 ± 2.3	2.51 ± 0.03	0.227 ± 0.036 B	0.0502 ± 0.0079 A b	1.73 ± 0.30 A b

[1] RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.

EC, electric conductivity; CEC, cation exchange capacity; PD, particle density; PAWC, plant available water capacity; MacP, macro-porosity; SI, stability index. Different letters in each column mean statistically significant differences at $P < 0.05$ using DMRT; A, B, C are the significant differences among the cropping systems for each depth; a, b, c are the significant differences among the depths within the cropping system. Numbers following the ± symbol represent the standard deviations.

Table 7. 3 Influence of crop rotations on selected soil physical quality indicators and parameters for the overall 0-30 cm depth[1].

Cropping system	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	BD (Mg m^{-3})	PD (Mg m^{-3})	SP (%)	PAWC (m^3 m^{-3})	MacP (m^3 m^{-3})	SI
RRR	18.2	306.2	675.6	1.13 A	2.50	54.9 B	0.225 B	0.036 C	1.22 C
RUR	17.5	304.8	677.5	1.09 B	2.51	56.7 A	0.246 A	0.047 B	1.36 C
RUU	23.1	312.9	663.8	1.07 B	2.51	57.1 A	0.258 A	0.050 B	1.54 B
UUU	18.1	303.6	678.2	1.11 AB	2.50	55.7 AB	0.227 B	0.057 A	1.99 A

[1] RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.

BD, bulk density; PD, particle density; SP, soil porosity; PAWC, plant available water capacity; MacP, macro-porosity; SI, stability index. Different upper case letters in each column mean statistically significant differences (P < 0.05, using DMRT) among the cropping systems.

Table 7. 4 Influence of crop rotations on selected soil chemical quality indicators and parameters for the overall 0-30 cm depth[1].

Cropping system	pH (-)	EC (µS cm^{-1})	CEC (cmol+ kg^{-1})	SOC (g kg^{-1})	SOC stocks (t ha^{-1})	$C_{hydrolysable}$ (g kg^{-1})	$C_{hydrolysable}$ stocks (t ha^{-1})
RRR	5.44	623	24.4	21.2 A	66.42 A	0.97 B	3.01 B
RUR	5.50	624	23.5	22.6 A	72.26 A	1.69 A	5.44 A
RUU	5.56	541	24.5	21.5 A	68.30 A	1.79 A	5.71 A
UUU	5.57	503	23.9	17.9 B	59.31 B	1.72 A	5.72 A

[1] RRR, rice-rice-rice; RUR, rice-upland crop-rice rotation; RUU, rice- upland crop - upland crop rotation; UUU, upland crop- upland crop- upland crop rotation.

EC, electric conductivity; CEC, cation exchange capacity; SOC, soil organic carbon; $C_{hydrolysable}$, HCl-hydrolysable soil carbon. Different upper case letters in each column mean statistically significant differences (P < 0.05, using DMRT) among the cropping systems.

7.4 Discussion

Five years after replacing long-term rice monoculture having three rice crops per year (RRR) with rice-upland crop rotations (RUR and RUU) or continuous cultivation of upland crops (UUU), effective changes in SOC content were observed among cropping systems as well as among the depths within cropping systems. At the 20-30 cm depth, RUR, RUU or UUU had significantly higher SOC ($P < 0.05$) than did RRR, and an opposite trend occurred at the 0-10 cm depth with the highest SOC value found under RRR. This could be explained by the deeper tillage (0-30 cm depth) and hence the greater soil mixing during the upland crop season in comparison with rice monoculture (0-10 cm depth only). Breaking up the hardpan and mixing the soil likely resulted in greater crop residue input at a depth of 20-30 cm under the RUR, RUU and UUU systems than under RRR. Further, rice is most frequently grown under flood irrigated conditions, where the upper part of the soil profile is completely saturated (Norman et al., 2003). This reduces the mineralization rate thus slowing down the decomposition of fibrous residues as has been reported by Olk et al. (2009b), which causes the accumulation of soil organic matter, especially at the depth of 0-10 cm. This may reduce nitrogen mineralization due to phenol accumulation in flooded rice soil (Olk et al., 1996; Cassman et al., 1997).

Throughout the entire 0-30 cm depth, there were no significant differences in SOC stock when shifting from RRR to the RUR and RUU systems. However, of major concern is that changing long-term RRR to UUU caused a decrease in SOC stock: UUU had significantly less SOC content (17.9 g kg^{-1}) than did RRR, RUR and RUU (21.2-22.6 g kg^{-1}) (Table 7.4) over the top 30 cm. According to the farmers, nearly all aboveground biomass from the upland crops was collected after harvest, resulting in very limited addition of crop residues to the soil. In contrast, addition of organic residue in the form of crop residue was greater after the rice crop season, with crop residue (rice stubble) remaining on the soil surface for incorporation before the subsequent crop season. Furthermore, changes in the soil environment associated with year-round aerobic conditions under UUU might have contributed to accelerated organic residue decomposition, causing rapid breakdown of accumulated soil organic matter and thus low SOC accumulation. Guo and Gifford (2002) reported that changes in land use are necessarily followed by changes in soil carbon storage. Soil organic carbon stock under the rotation system of two rice with one upland crop seasons per year did not differ significantly from that of rice with two upland crop seasons per year. In our study, this rotation was only applied for five years, so this limited duration might be the reason for not finding differences in SOC content between RUR and RUU.

The $C_{hydrolysable}$ values did not show a similar trend with SOC for all cropping systems. Despite a much larger SOC content in RRR at the 0-10 cm depth, $C_{hydrolysable}$ did not significantly differ from that of other cropping systems (Fig. 7.1). Averaged across the 0-30 cm depth, the ratio of $C_{hydrolysable}$ to SOC was more than 70-80% greater in RUR and RUU than in RRR (Fig. 7.2). Remarkably, the proportion of $C_{hydrolysable}$ to SOC was for UUU (9.5%) more than two times that under continuous rice monoculture (4.5%). This heightened proportion of hydrolysable C could reflect more frequent soil disturbance coupled with the aerobic soil conditions prevailing during the upland crop seasons, hence, enhanced microbial activity which stimulates the decomposition of organic residues in rotation systems with upland crops (Dung et al., 2010; Xuan et al., 2012). Our results are consistent with those of Xu et al. (2007) who reported that the relative rate of soil organic matter decomposition generally increases under frequent alternation between anaerobic and aerobic conditions (Pulleman et al., 2000; Norman et al., 2003).

Increasing the organic matter stock as well as organic matter decomposability (i.e. $C_{hydrolysable}$) through rotation of rice with upland crops might contribute to the increase in soil physical quality (i.e., BD, PO, PR, PAWC, MacP and SI). After five years of rice-upland crop rotations, soil BD at the 20-30 cm depth was 9% and 12% lower under RUR (1.22 g cm^{-3}) and RUU (1.17 g cm^{-3}), respectively than under RRR (1.33 g cm^{-3}) (Fig. 7.3a). Relative to the other cropping system, UUU had the greatest BD in the surface soil (0-10 cm), while BD at the 10-20 cm and 20-30 cm depths was greatest in RRR ($P < 0.05$) coinciding with a hard pan. Along with bulk density, soil penetration resistance was lower at the 20-30 cm depth in rice with upland crop rotations (Fig. 7.4). These systems returned more organic residues to the subsoil (below 10 cm depth), whereas in RRR, this return occurs primarily in the topsoil. This difference can be explained by seasonal plowing and puddling, and repeated machinery trafficking (Mahboubi et al., 1993) under wet conditions that characterize RRR. With degradation of soil structure under such challenging conditions as with RRR, the soil BD increased and compaction occurred at 20-30 cm. The soil of the study area had high clay content (>60%) and may therefore be sensitive to compaction. It is clear in Figure 7.3a that the BD in rice and upland crop rotations (RUR and RUU) and upland crop monoculture (UUU) was not only above the optimum range for field crop production but also below the upper limit for soil compaction in fine textured soil (0.9-1.2 Mg m^{-3}). According to Jones et al. (2003) the threshold bulk density for soil compaction for these soils with clay content of ~650 g kg^{-1} is ~1.2 Mg m^{-3} ($BD_{threshold}$ = 1.75 Mg m^{-3} – 0.9Cl, where Cl is clay content in g g^{-1}). This threshold value was clearly exceeded in RRR at 20-30 cm depth, whereas RUR, RUU and UUU showed BD values close to the threshold. Soil compaction at 20-30 cm depth under the RRR system can impede mechanical rice root penetration in the soil and hence inhibit deep rooting (Chapter 5). According to local farmers, under the RRR system rice plants can lodge in the ripening phase, which makes harvest difficult and results in yield loss. This was less the case in the other cropping systems (i.e., RUR, RUU and UUU) which received a lower number of machinery passes compared to RRR. Furthermore, rotations with upland crops provide a deeper and higher degree of soil mixing and thus bulk density showed little variation with depth and was significantly lower at 20-30 cm depth than in rice monoculture. Other researchers found that deep tillage reduces soil penetration resistance and thus promotes deep rooting (Kundu et al., 1996; Khan et al., 1998).

Correlation analysis showed that SOC was aggrading with increasing soil porosity and decreasing soil bulk density. We observed a rather high positive correlation of SOC with SP with r = 0.79, and consequently a negative correlation with BD with r = -0.80 ($P < 0.01$) (Fig. 7.5 and Fig. 7.6). Negative correlation between organic carbon and bulk density were also observed by Cotching et al. (2002), Reynolds et al. (2007) and Diana et al. (2008). However, there was low correlation between soil organic matter content and aggregate stability index. The low correlation may be due to independent effects on aggregate stability by specific organic components rather than the bulk soil organic matter (Lal and Shukla, 2004).

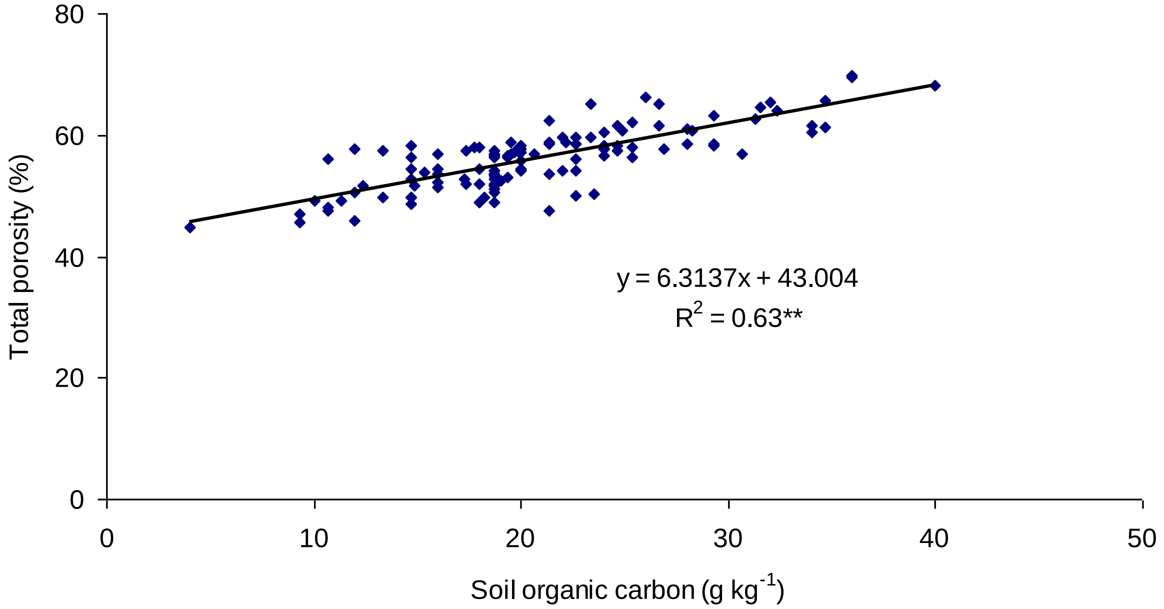


Figure 7. 5. Regression equation and coefficient of determination (R^2) describing the relationship between soil porosity and soil organic carbon.

The asterisks (**) indicate the significance of R^2 at $P < 0.01$.

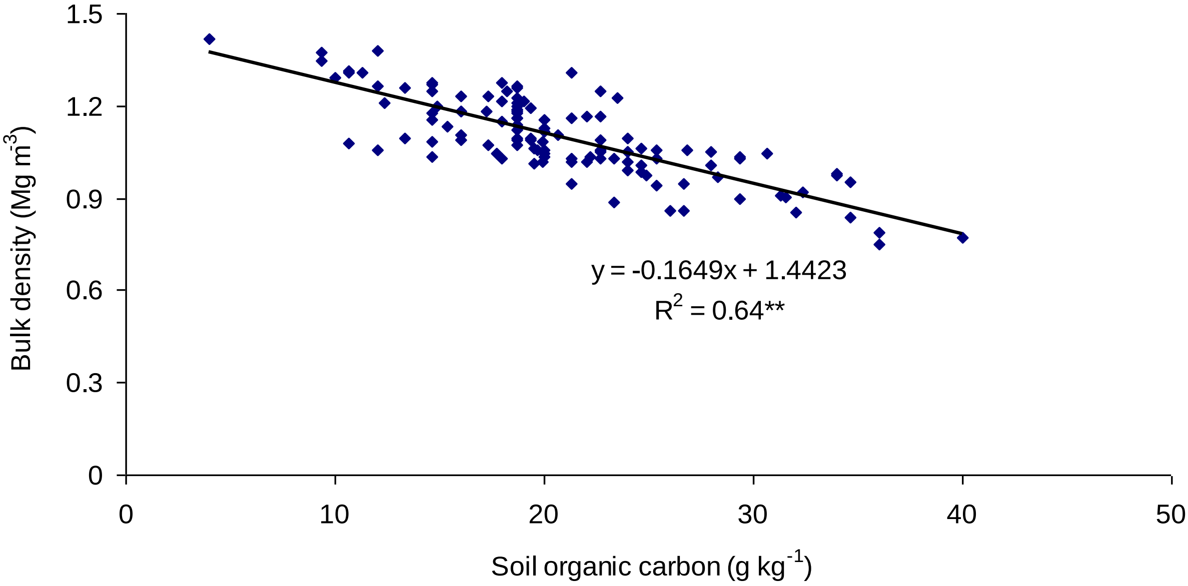


Figure 7. 6 Regression equation and coefficient of determination (R^2) describing the relationship between soil bulk density and soil organic carbon.

The asterisks (**) indicate the significance of R^2 at $P < 0.01$.

Increased compaction probably reduced PAWC, SI and MacP in RRR. RUR, RUU and UUU had greater SI values than did RRR by 11 to 63% (Table 7.3). An increase in aeration in the upland crop season(s) likely caused the increased SI. With three puddling operations per year under wet conditions and prolonged flooded conditions during the rice season of the RRR, this probably promotes the dispersion of soil aggregates (Hillel, 2004) and thus lowers the aggregate stability index. RRR also produced some differences in MacP at the 20-30 cm depth. While the other cropping systems yielded a large MacP (0.0417-0.0522 m^3 m^{-3}), the RRR value was about 60-70% smaller (0.0281 m^3 m^{-3}) (Table 7.3). The higher MacP at depth under the RUR and RUU systems might be attributable to the increase in SOC, which in turn led to increased SI which generally results in additional total pore space. Moreover, deeper soil preparation and a coarse root system of upland crops in UUU, RUR and RUU would favor the creation of macropores and thus increasing SP. This scenario is consistent with the documented gain of SOC causing a rapid and significant increase in MacP (Carter, 1990). The low PAWC under RRR relative to RUR and RUU appears to be due primarily to a decrease in the number of pores, which is consistent with the low matrix porosity of RRR relative to the other cropping systems.

Surprisingly, UUU produced a SI and MacP that were much greater than that of RRR, RUR and RUU, although SOC stock of this system was lower than that of RRR, RUR and RUU ($P < 0.05$) (Table 7.4). The soil physical properties of the UUU system did generally not deteriorate five years after replacing continuous rice monoculture with continuous upland crop monoculture and its soil quality indicator values still fell within ideal ranges as presented by Reynolds et al. (2007), although it caused a decrease in SOC content. This decline can reduce soil productivity in the future if the farmers do not apply organic fertilizer or keep crop residue on the fields after harvesting.

Several soil properties in this study, including pH, CEC, particle size distribution (sand, silt and clay) and soil particle density were not affected by changing the cropping system from RRR to RUR, RUU and UUU (Tables 7.2 and 7.4). The significant differences in SOC content but equal CEC among cropping systems points to the limited contribution of soil organic matter to soil CEC in these clayey soils with high clay content (~65%). However, EC trended downward in UUU at 0-10 cm depth and also over 0-30 cm depth, probably reflecting enhanced eluviation of nutrients from the soil beds.

Yet, with introduction of rice-upland crop rotation systems, several soil properties that are often considered as indices of soil quality improved within five years. Limited soil compaction reflected by bulk density and penetration resistance, and greater soil organic carbon quality expressed in terms of $C_{hydrolysable}$ might have explained the higher rice grain yield and income observed in rice-upland crop rotation systems in a farm household survey with 109 farmers on the same fields where the present study was conducted (Chapter 8). The significance of soil physical properties to rice yields and net profitability in experimental field was also highlighted in Chapter 4 and 5. They concluded that soil physical properties contributed to enhanced rice yield with rice-upland crop rotation systems. In these systems, the improved soil physical properties increased rooting depth and rice yield compared to the rice monoculture system.

On the other hand, other factors can also contribute to rice yield problem with RRR such as inhibited N supply. Cassman et al. (1997) discussed the complete reversal of a long-term yield decline in similar RRR fields in the Philippines by better synchronizing N fertilizer application with plant N demand, which compensated for decreasing availability of soil N. The yield reversal occurred despite no effort to improve the physical properties of those soils. Presuming that soil N supply is therefore a key contributor to the long-term yield decline, we speculate that rotation with an upland crop and resulting improvement of soil physical properties would facilitate a long-term yield reversal by enabling the root system to access deeper soil masses and their N supply. Increased soil aeration during upland crop rotation can in cases also improve soil N mineralization and rice crop uptake of soil N (Olk et al., 2009a). Accordingly, many continuous rice farmers in Asia drain their fields sometimes during the growing season with the belief that the aeration improves soil rooting depth or increases crop N uptake (Kaneta et al., 1989).

7.5 Conclusions

After five years of alternative cropping systems with rotations of rice with upland crops on clay soil, several soil physical and chemical properties were changed in small scale farmers' fields. The soil quality of the RRR system was the poorest in relation to the major soil function in the area, i.e, sustainable rice production. Soil quality improved with rotation of rice with upland crops, showing higher SP, $C_{hydrolysable}$, PAWC, MacP and SI, and lower BD and PR, especially at the 20-30 cm depth. Overall, those rotation systems resulted in a reduction in soil compaction and improvement in soil structure, which may results from mixing the soil for bed preparation and better organic carbon quality in terms of higher $C_{hydrolysable}$ contents as compared to long-term rice monoculture. However, although UUU showed no compaction, it produced 10, 15 and 18% less SOC stocks than RRR, RUR and RUU, respectively, suggesting the potential of the UUU system for degrading soil organic carbon. Our results may lead to increased awareness and development of more sustainable agricultural practices that can lead to less degraded soil for future productivity.

Chapter 8

Socio-economic evaluation on how crop rotations on clayey soils affect rice yield and farmers' income[#]

This chapter is based on:

Linh, T.B., Cornelis, W., Sara, V.E., Khoa, L.V., 2013. Socio-economic evaluation on how crop rotations on clayed soils affect rice yield and farmers' income in the Mekong Delta, Vietnam. International Journal of Environmental and Rural Development 4-2, 62-68.

8.1 Introduction

Agricultural production in the Mekong Delta is based on private smallholding. Farming in the delta is strongly rice oriented (Xuan and Matsui, 1998). They are suitable for rice production and continuous rice cultivation is the dominant cropping pattern. However, after long-term practicing triple rice cropping, the land use system exposed its negative effects on soil quality and crop production. Long-term practicing of continuous cultivation is the main cause of degraded physical and chemical soil properties (Acosta et al., 2004; Achmad et al., 2003; Cotching et al., 2002). One of the most prominent types of soil degradation is soil compaction, which mainly originated from rice cultivation with high soil rotation and increased mechanization under wet conditions (Lima et al., 2009).

Results in chapter 7 showed that rice-upland crop systems in farmer's fields can help in alleviating soil compaction and soil organic residues decomposition resulting from continuous mono cultivation systems. The objectives of this study are evaluate how farm characteristics and crop rotations of rice and upland crops affect crop yield and income, as well as identify the major problems that farmers face. Our research will be helpful to provide basic information for farmers, agricultural extension agents, policy makers, local authorities and consultants to make appropriate land management decisions in order to conserve the natural land resources and support sustainable agricultural production.

8.2 Methodology

The study area description was previously presented in Chapter 1 section 1.5.

A total of 109 farm households (one type of cropping system for one farmer field) were interviewed using structured questionnaires. For the cultivation of 3 upland crops per year, 19 farmers were interviewed and for the other cultivations, 30 farmers were interviewed. The surveyed farms were randomly selected. In the interviews, sheets with following information were collected: history of people's settlement and exploitation, and crop rotation system development; cropping pattern and types of cultivation; cultivation techniques and land management like soil preparation for cultivation, application of fertilizers, irrigation and drainage, limiting factors of plant yield and soil productivity and rice yield and total cost of cultivation for calculating economic efficiency of the different cropping system practices.

Analyses of differences between the means were tested using SPSS 20. Significant differences were determined using the Duncan multiple range test at 5% significance level.

8.3 Results and discussion

8.3.1 Present land use systems and cultivation practices

Interview results show that upland crops are normally cultivated on raised beds, with the soil dug to 30 cm depth for making raised beds and furrows. Meanwhile, rice is planted on flat fields after plowing and puddling with a small tractor for every rice crop season. Current canal systems which are carrying the fresh water irrigation and dike systems preventing flood water, farmers are able to cultivate 3 crops a year, i.e. a winter-spring season (from November to February), a spring-summer season (from March to June) and summer-autumn season (from July to October). Inorganic fertilizers such as DAP, Urea, Superphosphate, Potassium chloride, NPK20-20-15, NPK16-16-8 are broadcasted by hand. Organic manures are not applied. Rotations of rice with upland crops have been practiced for five years on fields that have subsoil compaction problems, which resulted in decreased rice yield even though farmers apply higher doses of fertilizer.

After harvest, rice crop residues (roots + stubble) were left on the field. The rice straw was used for mushroom cultivation or as cattle feed. Nearly all above ground biomass from the upland crops was removed to facilitate land preparation for the next crop. Some farmers dried their rice produces first and stored them for a while. After some time, when the household needs cash or when prices do rise they may take the products out of store to sell (average selling price is 10-20% higher at harvest). More than 80% of the farms sell their products directly to buyers after harvest.

The sowing density of rice in RRR is higher in comparison with RUR and RUU (Table 8.1). In the winter-spring season, about 57% of the surveyed farmers in RRR used 100 to 150kg seeds ha^{-1}, and 43% used 150 to 200 kg ha^{-1}, whereas this was 73% and 27% for RUR, and 83% and 17% for RUU, respectively. In the summer-autumn seasons about 23% of the surveyed farmers in RRR used 100 to 150kg seeds ha^{-1}, and 77% used 150 to 200 kg ha^{-1}. For RUR, this was 53% and 47%, respectively.

Table 8. 1 Percentage (%) of the surveyed farmers using given rice seed amount

Rice seed amount (kg ha^{-1})	Winter-Spring			Summer-Autumn	
	RRR	RUR	RUU	RRR	RUR
100-150	57	73	83	23	53
150-200	43	27	17	77	47

RRR: rice-rice-rice; RUR: rice-upland crop-rice rotation; RUU: rice-upland crop-upland crop rotation.

Regarding fertilizer application for rice growing, the optimum fertilizer level for this area is 100 kg N ha^{-1} (Guong and Linh, 2008). The results of the survey revealed that farmers in RRR had a tendency to apply rather high doses of N as a way to compensate for the reduced rice growth and rice yield resulting from land degradation. N fertilizer application of 77% of the surveyed farmers in winter-spring season and 63% in summer-autumn in RRR system was over the recommended dosage, ranging from 101 to 130 kg N ha^{-1} crop^{-1} season. This is remarkably higher as compared to RUR and RUU (Table 8.2). Although, farmers apply less fertilizer and pesticides in rice-upland crops rotation systems for rice production compared to RRR, the rice yield was higher for RUR and RUU than for RRR (Figure 8.2). According to the farmers, when they apply N in doses like in past seasons, the rice plant shows dense leaves. It becomes more attractive to insects and diseases. It can also cause excessive growth and reduce the strength of the stems and hence falling down at grain filling stage. Therefore, the farmers apply lower doses of N in case of RUR and RUU rotations. The heavy inorganic fertilizer and pesticide use in RRR might further causes water pollution and unbalanced rice field ecology.

Table 8. 2 Percentage (%) of the surveyed farmers that applied the indicated fertilizer doses to the rice crop.

Type	Fertilizer amount (kg ha^{-1})	Winter-Spring			Summer-Autumn	
		RRR	RUR	RUU	RRR	RUR
N	70-80	0	17	30	7	23
	81-90	13	30	47	17	53
	91-100	10	43	23	13	17
	101-110	50	7	0	33	7
	110-120	20	3	0	30	0
	121-130	7	0	0	0	0
P_2O_5	40-50	10	7	10	10	10
	51-60	10	17	20	7	23
	61-70	40	50	57	30	53
	71-80	27	20	7	30	13
	81-90	10	3	6	20	0
	90-100	3	3	0	3	0
K_2O	5-10	20	17	17	13	13
	11-20	43	33	27	33	30
	21-30	23	27	30	33	43
	31-40	7	13	17	13	7
	41-50	3	7	10	7	7
	51-60	3	3	0	0	0

RRR: rice-rice-rice; RUR: rice-upland crop-rice rotation; RUU: rice-upland crop-upland crop rotation; UUU: upland crop-upland crop-upland crop.

8.3.2 Farm size

The average area under cultivation per farmer for the different rotations is shown in Figure 8.1. Agricultural production in Cai Lay is based on private smallholding with an average farm size of less than 1 ha. The average farm size in the study area is about 0.62 ha. The farm size of the RRR system ranged from 0.45 to 2.50 ha with an average of 0.91 ha. The average size of small farms is 0.36 ha and such small farms are found in UUU systems. Farms of average size of 0.68 ha and 0.43 ha are found in RUR and RUU systems, respectively. The RUU and UUU system was practiced on significantly smaller farm as compared to RRR (P < 0.05).

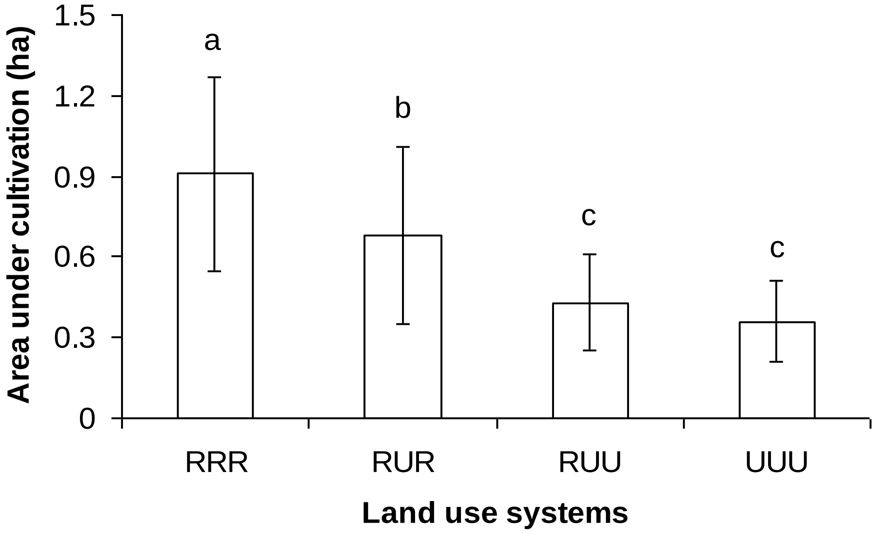
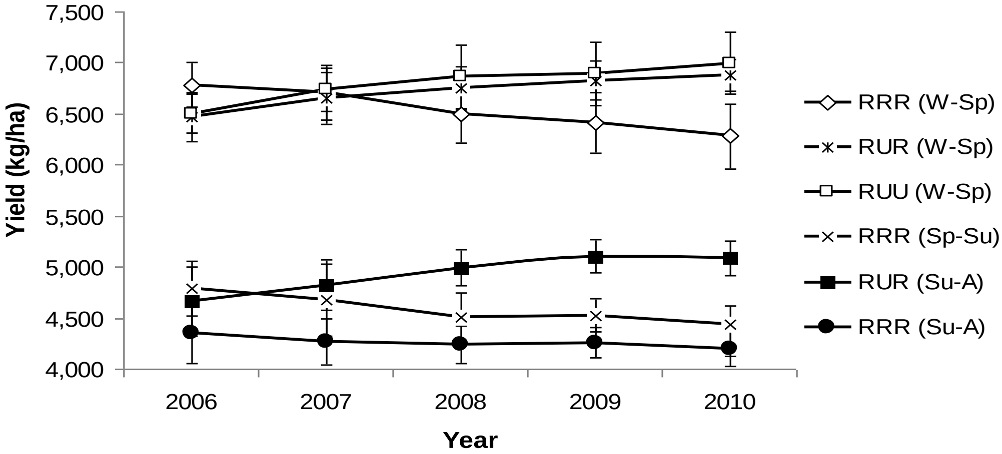


Figure 8. 1 Average area under cultivation per farmer (ha) for the different cropping systems

Farmers who choose rice monoculture cropping system have a large part of their land under cultivation in contrast with the small scale farmers who seemed to adopt a strategy of diversification. The diversification of the farming system corresponds to a strategy by small scale farmer to stabilize their economic situation and improve their soil. Nevertheless, it is expected that their economic situation is threatened because of the tendentious depreciation of rice yield. Farmers who cultivate mono rice does not like to replace with another crop because of the high investment, the market price of upland crops is not being stable and the limited storage possibilities for their produce if they cannot sell it immediately after harvesting.

8.3.3 Rice yield evolution

Based on the interviews with local farmers in the study area, the following information on rice crop yield was collected (Fig. 8.2). It was shown that rice yield is different among farmer groups. Farmers of rotation groups RUR or RUU obtained much higher rice yields than RRR system. The mean difference was statistically significant in all seasons. Rice yields were significantly different ($P < 0.05$) among the systems of RRR (6.3 ton/ha) and RUR (6.9 ton/ha) or RUU (7.0 ton/ha) in winter-spring season and among the systems of RRR (4.2 ton/ha) and RUR (5.1 ton/ha) in summer-autumn season. Besides that, rice yield in the last five years increased when rotations with upland crops were implemented (RUR and RUU), with for RUR an increase of 9% for summer-autumn season and with 6% for winter-spring season, and for RUU an increase of 8% for winter-spring. This was strongly in contrast with the rice yield decrease for rice monoculture systems (RRR), which showed a decrease of 8%. The yield increase in the rice-upland crop rotations can be associated with alleviated soil compaction (Chapter 7) and improved root zone by change in depth of the plow pan layer, so that roots can grow deeper in the rotation systems with upland crops. The rice monocultures recorded the lowest yield because of, according to the farmers, reduce soil fertility, soils becoming compacted, falling down of rice after flowering, and frequent outbreaks of insects and diseases.



W–Sp: Winter-Spring; Sp –Su: Spring-Summer; Su–A: Summer-Autumn

Figure 8. 2 Rice yields within recent-past 5 years for the different cropping systems.

There was also a large variation in rice yield over seasons was observed. The rice yield was much higher for winter-spring rice than for the spring-summer or summer-autumn cropping period (Fig. 8.2). In the winter-spring season, rice showed much higher yield on average of five years (6.5; 6.7 and 6.8 ton ha^{-1} for RRR, RUR and RUU, respectively) as compared to spring-summer (4.6 ton ha^{-1} for RRR) and summer-autumn seasons (4.3 and 4.9 ton ha^{-1} for RRR and RUR, respectively). This may be due to the better climatic conditions with planting just after the flood season, higher solar radiation and adequacy of irrigation water and is the reason why rice is preferably cultivated in the winter-spring period. According to the farmers, the weather, disease and insect pests are the major cause of yield loss in rice production in the spring-summer and summer-autumn seasons.

8.3.4 Economic evaluation

The total economical balance for each land use system was analyzed based on a 1 ha farm size. The production costs like those for seeds and materials, fertilizer, labor and pesticide constitute an important part of the total variable cost of the system. Figure 8.3 shows the costs for seeds and materials, fertilizers, pesticides and labor on the one hand (input) and income on the other (output) with total profit the difference between both for the different land use practices. The total cost of upland crop monoculture (UUU) and rice-upland crop rotation systems (RUR and RUU) were significantly higher than those of RRR farms. This result is consistent with the findings of Nguyen (2010) in a rice-upland crop survey conducted in Cho Moi district, An Giang province.

For the whole sample, labor cost is the main input contributing about 56% of the total production cost, followed by fertilizer (26%), pesticide (13%) and seed (6%). Although most farmers have enough family laborers for rice production, most farmers hired labor for seasonal activities. On average, the hired labor cost contributed about 40-45% of the total labor cost. On the whole, the production cost in the wet seasons is higher than that in the dry season. Usually, wet fields are more difficult to work, especially for harvesting. Harvesting of the wet season crop occurs at a time of heavy rains so that farmers face serious problems for postharvest activities such as drying, cleaning and hauling. The labor requirement for harvesting and post harvesting also increases in function of the increased output.

The contribution of seeds and materials to the total cost is low (7%) for RUR and RUU. Fertilizer application accounts for 21 to 23% of the total cost for RUU and RUR, respectively. Labor manifests the highest contribution to the total cost (61-62% of total cost). The use of upland crops in the rotations creates more labor because of the need for raised beds that have to be dug. This makes the total cost to increase with increasing use of upland crops in the rotation. In rice-upland crops rotation systems, farmers apply less fertilizer and pesticide for rice production so that the rotation with one or two upland crop shows the lowest costs for fertilizer and pesticides for rice crop. Indeed, the interruption of the rice cultivation by an upland crop can break off the food supply for rice specific pests (especially soil-borne diseases) and decreases the need for pesticides. In addition, fertilizer applications are often below the normal levels, especially N. The farmers said that when rice receives too much N, it becomes more attractive to insects and diseases. It can also cause excessive growth and reduce the strength of the stems and falling of the plant.

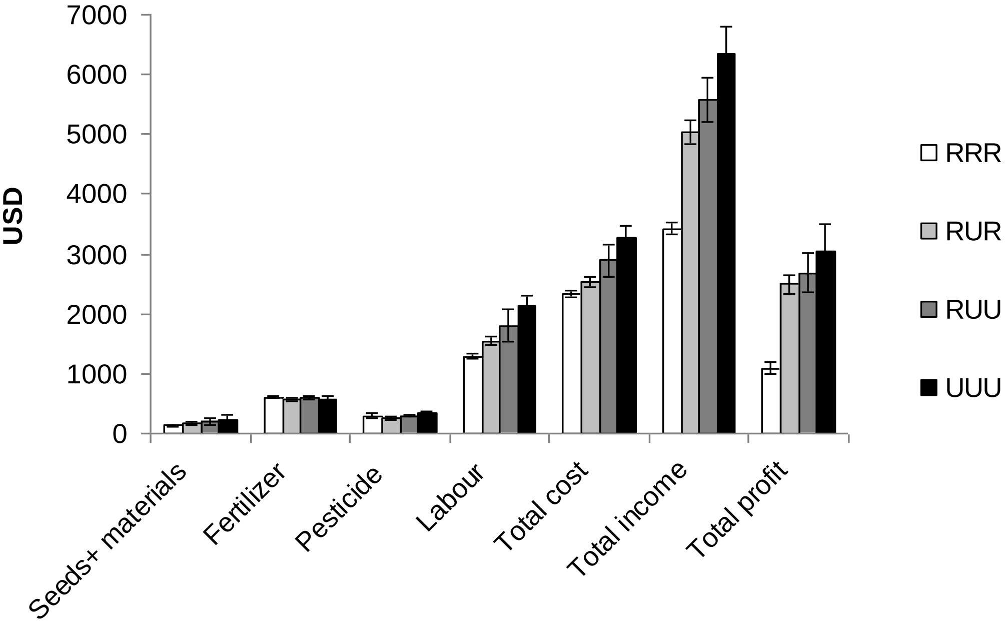


Figure 8. 3 Cost and income for the different cropping systems (in USD)

Farmers practicing rice monoculture generally receive a lower farm income per hectare than those applying rotated farming systems, per year or and per season. In other words, farmers growing other crop rotations with rice or monocultures of upland crops can receive a higher income. The total income is highest for UUU, followed by RUU and RUR, and finally RRR per season and per year. The total income of RUR and RUU was 5,025 USD/ha/year and 5,575 USD/ha/year, respectively. Those were higher than the net income of RRR (3,424 USD/ha/year), but significantly lower than the net income from the UUU system (6,338 USD/ha/year). On the other hand, there were large total profit differences among the cropping systems. The profit of rice-upland crop rotation systems (RUR and RUU) was more than two times higher than that of rice monoculture system (RRR). The profit of upland crop monoculture (UUU) was almost three times higher than RRR system. Indeed, the total profit of RRR was only 1,094 USD/ha/year, whereas the UUU farmers gained a very high 3,058 USD/ha/year, and RUR and RUU farmers a modest 2,490 USD/ha/year and 2,686 USD/ha/year, respectively.

Table 8. 3 Benefit-costs ratio for different land use systems.

Cropping system	RRR	RUR	RUU	UUU
Winter-Spring	0.86d	1.24b	1.35a	1.15c
Spring-Summer	0.09b	0.82a	0.88a	0.90a
Summer-Autumn	0.45c	0.98a	0.78b	0.76b
Whole year	0.47b	0.98a	1.00a	0.93a

Within rows, values followed by the same letter are not significantly different at $P < 0.05$

Result showed that the costs-benefit ratio (B/C) in rice-upland crop rotation systems was higher than in traditional rice monoculture system (Table 8.3). The B/C shows that rice monoculture has the lowest profit over costs (46 to 51% lower than the other cropping systems) and that RUU is the most successful with B/C 100%. Although there was not significance in B/C between RUR and RUU, they were significantly higher than that of the RRR system.

Compared to rice monocultures, rotations of rice and upland crops give higher values of farm diversity and economic efficiency. The rice-upland crop systems are therefore more ecologically sustainable than rice monoculture systems. However, according to the local farmers, occasional low market prices for the crop product (when the selling price is below the cost of producing the product), lack of capital investment, low level of technological skills, and unfavorable marketing system, among others, are major constraints for rotated rice-upland crops systems in the target area. Moreover, farmers who cultivate upland crops have to face low prices at the farm gate, since upland crops, especially vegetables are quickly damaged after harvest. In order to help the farmers, better models of farmer organizations should be developed. An appropriate and efficient credit scheme and upland crop farming technique training are urgently suggested to improve and widely develop rotated rice-upland crop systems in this area.

8.4 Conclusions

Rice yield in alluvial deposits with a clay texture was found to be lower in rice monocultures (RRR), than in rotation systems with upland crops (RUR or RUU) which both showed similar high rice yield. Applying upland crops to paddy fields can positively enhance the biodiversity, crop products and increase farmers' income. The cost benefit ratio was highest for rotations upland crop with rice cultivations. It also assures a lower application rate of agro-chemical in rotation systems. Total income was highest in upland crop monocultures (UUU), followed by RUR and RUU, with significantly lowest values for RRR. Our study showed that replacing the practice of rice monocultures with rotations with upland crops is very promising. Farmers who adopt new cropping systems not only generate more goods for the society, but also more income for their family and more protection of land resources. The expansion of rice rotated with upland crops should be encouraged to increase income, effective utilization of labor and improve the soil quality. However, for national food security, and to sustain rice production, farmers should be encouraged to cultivate two rice crops and one upland crop per year.

Chapter 9

General discussion, conclusion and future research

9.1 Introduction

In recent years, it has been observed that declining paddy soil quality resulted in reduced rice yield and threatened the sustainability of conventional rice production systems in the Mekong Delta. Despite the efforts of farmers to maintain or even increase rice yield by applying more chemical fertilizer, rice yield tends to decrease. Given that cropping systems can affect soil quality, the main aim of this study was to evaluate the effect of new cropping systems in which rice was rotated with upland crops (maize and mung bean) on physical and chemical properties of paddy alluvial clay soil in the Vietnamese Mekong Delta, and thus to investigate to what extent those cropping system are soil improving.

In addition, long-term impacts of the new cropping systems on rice crop parameters and on economic productivity were analyzed to assess their feasibility and sustainability, which is important when towards farmer adoption. To that end, a 10-year field experiment (including 30 crop seasons) was conducted in Cai Lay district, Tien Giang province. Additionally, soil samples and socio-economic data were collected from farmers' fields spread over more than 100 households. The investigated cropping systems included rice monocultures with three rice crops per year (R-R-R), and rotations with one (R-M-R, R-Mb-R) or two (R-Mb-M) upland crops per year on the experimental site or even with three upland crops on farmers' fields (UUU, vs RRR, RUR and RUU).

This chapter summarizes the main findings reported in the different chapters and presents several recommendations for extension and future research.

9.2 Crop rotation effect on paddy soil properties

Our study showed that in the rice monoculture system subsoil compaction was present and associated with the frequent shallow plowing and puddling till around 15 cm depth carried out every rice crop season before sowing. This kind of repeated soil puddling causes dispersion of soil particles which upon settling tend to clog pores and thus reduce total porosity of soil. Additionally, the heavy machinery used for land preparation compresses the soil resulting in soil compaction from ~15 cm downwards. Although the hence developed compaction layer was aimed at to avoid water losses and thus keeping water in the rice flooding field at an optimal level, such form of shallow compacted layers aggravated cropland degradation leading to declined crop yield. The soil texture at the field experimental site was clay (65% clay and 34% silt), so it was vulnerable to soil compaction.

Unlike and in contrast with traditional rice monoculture systems, long-term consecutive crop rotations of rice with one or two upland crops resulted in a consistent reduction in soil degradation. Surely, our study demonstrated that cropping systems in which rice is rotated with maize and/or mung bean improve soil quality significantly in both dry and late wet seasons (Chapter 2, 3 and 4). Among the assessed soil chemical properties, soil organic carbon (SOC) at 20-30 cm depth and $C_{hydrolysable}$ at 0-30 cm depth showed the highest improvement. The rice monoculture system produced potentially excessive SOC in the soil surface, since submerged conditions prevailing throughout most part of the year reduced decomposition of organic residues leading to SOC accumulation. Although rice monocultures showed higher SOC content at a depth of 0-10 cm, it had a lower level of $C_{hydrolysable}$ since decomposition of rice residues was retarded by prolonged anaerobic conditions. In contrast, SOC at depths of 10-20 and 20-30 cm was significantly lower in rice monoculture compared to the rotation cropping systems. This may have impacted root penetration and less root-derived C inputs into the subsoil layer under R-R-R system was accordingly observed. The crop rotation system alleviated soil compaction resulting in the appropriate development of a deep and extensive root system of upland crop (maize/mung bean) and rice, and thus a high amount of root residues. On the other hand, the turning tillage operation under crop rotation systems resulted in direct incorporation of crop residue into the soil at 20-30 cm depth, resulting in higher subsoil OC content. This kind of SOC redistribution to deeper depth was just a secondary outcome of deeper tillage in rice-upland rotations. This aspect is very important due to the multiple roles played by the organic matter in the soil. Indeed, this improvement is consistent with the observed substantial increase in nitrogen (N), phosphorus (P) and potassium (K) (Chapter 5) and the change in stability index (SI), macro-porosity (MacP), plant available water content (PAWC) and Dexter's soil physical quality S index (Chapter 2, 3 and 4).

Additionally, conversion of long-term rice monoculture to rice-upland crop rotation systems ensured a progressive break up of part of the compacted layer, especially at 20-30 cm depth. This resulted in a decline of bulk density (BD) and penetration resistance (PR) or inversely, an increase in soil porosity (PO), which is highly sensitive to soil loosening. Moreover, it is also consistent with the increase in SOC as mentioned above.

Furthermore, rice with upland crop rotation systems not only alleviated persistent soil compaction but also created a more aerobic environment during the upland crop season which promoted crop residue decomposition. The generally much larger $C_{hydrolysable}$ produced by the rice-upland crop rotations probably reflects the disruption of the continuous anaerobic conditions, which facilitated crop residue decomposition. The improved decomposability of organic residues might have positively affected soil fertility by resulting in extra nutrient release through mineralization under the cropping systems with upland crops.

The results from the field experiments appear to reflect interactions among SOC and soil physical properties as BD, PO, PR, SI and MacP in the most compacted layer at 20-30 cm depth, with correlation coefficients of ~0.80 or higher ($P < 0.01$). The observed trends in soil organic carbon, soil bulk density and soil strength generally pointed to an improvement in soil structure (i.e. soil aggregate stability index) in both dry and wet cropping seasons. The soil structure improvement would result in increased macro-porosity, leading to the conclusion that soils with low compaction and high SOC content exhibit stable soil structure. However, further investigation would be needed to see if SOC storage in the rice-upland crop rotations is at least partly due to enhanced physical protection of organic matter occluded in finer aggregate size classes.

In addition, the stronger increase in BD and decline in MacP and field saturated hydraulic conductivity K_{fs} from the early stage of the cropping season (15 DASP) towards the middle and the end of the season (45 and 90 DASP) in rice monoculture system as compared to rice-upland crop rotations could be associated with aggregates being less stable as reflected by their lower soil aggregate stability index (Chapter 6). This confirms that plowing and puddling in rice monoculture system created a temporarily loose and fragmented, macro-pore rich soil in soil surface (0-10 cm) , which is, however, unstable and with a structure that is readily lost with time bringing it back to pre-tillage conditions.

Results from the farmers' field were less definitive as compared to those observed on the experimental field. Fewer soil properties were affected by the cropping systems, with differences for properties that were affected, being generally small, especially in two rice crops and one upland crop rotation system. This was probably so because the farmers' field study was conducted already after five years, and soil property changes were still at an early stage and hence could not cause much significant difference. In spite of this, the use of upland crops in the rotation caused significant improvement in soil organic residue decomposition and alleviated subsoil compaction compared to rice monoculture (Chapter 7).

9.3 New cropping systems effect on crop production and economic benefit

When evaluating the benefits of new cropping systems, crop yield is very important for farmers. Farmers may not accept the loss of crop yield, even though it would improve soil quality. Our study showed that improvements in soil chemical and physical properties facilitated rice growth and increased grain yield in rice-upland crop rotation systems as compared with rice monoculture, with maize as well as mung bean in rotations having a positive effect (Chapter 3, 4 and 5).

This positive effect was probably due to the change in depth of the plow pan layer, so that roots can grow deeper in the rotation systems with upland crops. Likewise, rice-upland crop rotation systems were found to enhance root biomass density by 62-71% over that observed in rice monoculture system, thereby resulting in greater below-ground biomass input in R-M-R, R-Mb-R and R-Mb-M. On the other hand, the root mass density was drastically reduced with depth in R-R-R, and particularly at 20-30 cm depth no root growth was observed. The limited root growth was associated with the higher soil bulk density and soil strength in R-R-R at depth of 20-30 cm as compared to the other cropping systems.

Deeper and denser roots resulted in higher root-zone nutrient stock available. Indeed, there was 1.11 to 1.94 times increase in the amount of macronutrients and micronutrients with the increase in the root zone in the upland crop-rice rotation system. The accumulation of some nutrients such as Ca, Mn, Si, Cu in the subsoil (20-30 cm) of the rice monoculture system can be explained by their limited uptake with shallow rice roots confined to the puddle layer (Chapter 5).

Better root distribution resulted in a higher number of tillers per square meter, grains per panicle and filled grains, and a larger rice height leading to higher crop biomass and grain yield under rice-upland crop rotation systems as compared to the rice monoculture system. The average rice yield over ten years was 18-27% higher in rotations with upland crops in both dry and late wet seasons, whereas in the 10th years, it was even 32 to 36% higher (Chapter 4 and 5). The additional availability of soil nutrients likely promoted rice yields relative to the control R-R-R system. This is indicated by significantly higher levels of P, K and several micronutrient elements in the rice rooting-zone. Improved rice growth and increased yields were not due to higher SOC stocks at 0-30 cm depth; in fact the 0-30 cm SOC stock in the R-Mb-M rotation was lower than in the R-R-R rotation (though not significantly), while the crop parameters and rice yield were much better in the R-Mb-M rotation. This demonstrates that content of SOC does not necessarily control rice growth and yield ($P > 0.05$). The higher $C_{hydrolysable}$ stocks nonetheless in the rice-upland crop rotations correlated positively with rice growth parameters. Since carbon is not a plant nutrient, possibly this relation was indirect via enhanced N-mineralization in soils having a more readily degradable SOM, but this requires further investigation. On the other hand, prolonged anaerobic conditions must have resulted in more frequent reduction of soil Fe and Mn in the R-R-R vs. the rice upland rotations. This may have more frequently lifted Fe and Mn in soil solution possibly until toxic levels, considering the relatively high level of plant-available Fe measured in soil extracts.

Although the soil properties and rice yield were affected by the cropping systems, we did not find significant differences in soil quality and in rice growth and yield between the two types of upland crops, i.e. the non-leguminous maize and the leguminous mung bean, nor between rotation systems with one or two upland crops. These results were supported by those from the farmer fields, which showed 10 to 11% and 21% higher rice yields in rotations with upland crops as compared to the rice monocultures in winter-spring and summer-autumn, respectively (Chapter 8).

Economic analysis can provide information about the feasibility and sustainability of a new practice for increased productivity and enhanced resource use efficiency in a given period. Generally, farmers' income was shown to increase significantly in the systems with upland crop rotations compared to rice monoculture. The cropping system, season or year did not affect the yield of maize or mung bean yield, i.e. similar maize yields were observed in R-Mb-M as in R-M-R from 2002 to 2012. This was also the case for mung bean (when comparing R-Mb-M and R-Mb-R). Therefore, the higher income in rice-upland crop rotation systems was mostly due to the higher rice yield and the selling price per kilogram of maize and mung bean being always higher than that of rice. Nevertheless, rotations with mung bean and maize cultivation showed a higher cost under any cropping season and over the whole agricultural year, because growing maize or mung bean is more labor intensive with raised beds to be prepared and both crops have a more demanding harvest as compared with rice. Such higher financial input is one of the biggest problems for the farmers, in that they do not have enough capital for proper investment. Even though total cost was higher in the rice-upland crop rotation systems, the benefit/cost ratio (B/C) was considerably improved in the 10th year of experiment (134% - 141%) as well as when calculated as an average of ten years (126% - 155%).

Besides and although not quantified in our study, rotations of rice and upland crops contribute to diversifying agricultural production rendering an ecologically more sustainable system than rice monocultures. Additionally, crop rotations might suppress soil borne pathogens, including fungi and nematodes and rotating crops with plants less susceptible to specific pathogens might cause a decline in the population of the pathogen due to natural mortality and the antagonistic activities of co-existent root zone microorganisms.

9.4 Does upland crop monoculture improve soil physical quality while keeping soil organic carbon content high?

Soil organic carbon stocks in farmers' fields were depleted and related to the number of upland crop seasons. Indeed, the SOC stock was significantly affected by the cropping system with the lowest value in UUU (Chapter 7). This result can be explained by the low amount of aboveground crop residue input per year in UUU as compared to the RRR, RUR and RUU systems. All residues of upland crops are removed to facilitate land preparation for the next crop, while rice straw stubble is left behind after harvest resulting in more crop residue input. On the other hand, decomposition of crop residue is limited and typically lower during the inundation period in the rice crop seasons which can favor the maintenance or increase of SOC. On the contrary, $C_{\text{hydrolysable}}$ stocks increased consistently with increasing number of upland crop seasons, owing to enhanced microbial activity with prolonged aerobic conditions, which favor faster organic matter decomposition rates.

The UUU system was therefore susceptible to loss of SOC if the farmers do not apply organic fertilizer. Such SOC decline can affect soil productivity and sustainability of this system in the long-term. From the farmers' field study, it could be concluded that cropping systems with rice-upland crop rotations are to be preferred over rice monocultures because of their higher soil organic carbon quantity and lower degree of soil compaction. Upland crop monocultures should not be promoted as they tend to reduce SOC content.

9.5 Critical limits for rice growth in the Vietnamese Mekong Delta

In this study, a variety of soil quality related physical and chemical properties were measured, with some of them showing a substantial response to the tested cropping system. The largest responses were found with BD and PR which were both negatively related with rice root growth and yield (Chapter 5). PO and MacP were positively related with crop growth and yield. However, “optimal” soil physical quality parameter values of clay soils for suitable rice crop production have not yet been defined, although various empirical guideline values have been proposed for growth of upland crops (Olness et al., 1998; Reynolds et al., 2002, 2007). Though not discussed earlier in previous chapters, in this general discussion we would like to suggest some values as indicative for optimal soil physical properties when growing rice in fine-textured alluvial soils, as a first step towards presenting real threshold values. To do so, soil properties were regressed with crop parameters and yield.

The highest rice yield as well as best root growth in our study corresponded with BD values in the most compacted layer lower than 1.2 Mg m^{-3}, PO higher than 51%, PR below 1.0 MPa and MacP higher than 0.04 m^3 m^{-3}. Under the R-R-R system, the roots grew only to a depth of 19 cm, while they penetrated deeper (till 27 cm) under rice-upland crop rotation systems, resulting in higher yields (Chapter 5). This would mean that for optimal root growth, highly compacted plow pans should not be present above 30 cm depth. According to Suzuki (2005) (cited in Reichert et al., 2009), under field conditions with clay soil (65% clay and 26% silt in his study), the critical value of BD and MacP that restricts root growth and reduces crop yield of soybean and corn was 1.36 Mg m^{-3} and 0.05 m^3 m^{-3}, respectively. No such quantitative limits are yet available for rice grown in clayey soil. Nie et al. (2010) observed that highly productive paddy soil possessed bulk density generally below 1.2 Mg m^{-3}.

Based on critical limits proposed by several authors for crops in general (Carter, 1988; Mambani et al., 1990; Thangaraj et al., 1990; Reynolds et al., 2007) BD and SP observed in this study for rice-upland crops rotations were within the optimal range for fine-textured soils, in contrast with the rice monoculture system. PR and MacP were close to these suggested limits. This suggests that the optimum values of some soil quality indicators proposed for crops in general seem to be valid for paddy rice soil as well. Based on the above values, we suggest to consider BD < 1.2 Mg m^{-3}, PO > 51%, PR < 1.0 MPa, MacP > 0.04 m^3 m^{-3}, and a root zone depth

> 30 cm as indicative for optimal physical soil quality when growing rice in fine-textured alluvial soils.

9.6 Future prospects and recommendation for sustainable rice production

After ten years of experimental work (30 cropping seasons) several effects of long-term crop rotations became clear in the paddy clay soil as discussed above. Rotations of rice with one or two upland crops improved SOC decomposition and physical properties since they were associated with frequent drying and wetting cycles and thus aerobic and anaerobic conditions. Our study showed that rice and upland crop rotations coupled with appropriate tillage are soil-improving cropping systems that need to receive more attention in the Mekong Delta in order to cope with soil degradation that was observed in continuous paddy monoculture areas and to maintain or even increase rice yield and farmer’s income. Although in the study area irrigation water for rice was always matching the demand, saving water would be possible if one or two rice crops are replaced with one or two upland crops which show a lower water requirement. Altogether, recommendations for the farmers to rotate rice with upland crops in their paddy soil, particularly in the region of intensive rice monoculture, in order to contribute to increased sustainable crop production need to be formulated.

Despite market prices varying over seasons and years, our findings provide evidence that including upland crops in paddy field could increase farmers’ income compared to traditional rice monoculture system. Indeed, the demand for vegetable and bean produce has increased enormously, hence upland crops show better market prices compared to rice. However, as rice is an important crop in the Mekong Delta, rice will continue to be the mainstay. To maintain national rice food security and to sustain rice production, farmers should be encouraged to cultivate two rice crops and one upland crop per year.

According to the planting calendar of the farmers in the study area, rice or upland crops can be sown every time of the year, i.e., in the winter-spring season (from November to February), spring-summer season (from March to June) and summer-autumn season (from July to October). The winter-spring cropping season is the best season due to the best climatic conditions with higher solar radiation and adequacy of irrigation water. The summer-autumn season is the wet season. Therefore, rice is most suitably cultivated in the winter-spring and summer-autumn period. Upland crops, that show lower water requirement - should then be cultivated during the dry months (spring-summer season).

According to the Department of Agriculture in the Cai Lay district, the area under rice-upland crop rotation practices recently increased. Though the adoption rate for such rotations is on the rise, still less than 10% of the rice producers accepted to change to this new cropping system. Farming experience and high farming costs for growing upland crops are two of the largest problems for adoption of rotation that make producers' unwillingness to accept change (Chapter 8). Indeed, many farmers interviewed in the study area faced a lack of technical skills and limited access to capital. As a result, when these households start up new crops, the sustainability of these activities may become problematic. On the other hand, without carefully planning and connection to the market there is a potential risk for market over supply of upland crop products. Therefore, it is very important for the government and local authorities to help farmers by providing information of upland crop cultivation techniques, marketing and business development. Rural credit policies could be redesigned in order to create more efficient access to the source of capital and as such contribute to improved livelihoods especially for farmers who adopt new cropping systems. Furthermore, insurance service such as crop insurance is needed to decrease some of the major risks that farmers face. Unfavorable market can be solved as well by making strategies targeting at community level or farmer organizations instead of individual farmers. If these problems are solved, it is believed that soil-improving cropping systems with upland crop-rice rotations not only help farmers to increase their income, but also contribute to rural development and sustainable agriculture.

9.7 Recommendation for future research

This dissertation has given new insights on the effects of crop rotations as compared to rice monocultures on soil physical and chemical properties and rice yield through a long-term field experiment. Additionally, relationships between soil properties, crop growths and economic benefits have been studied. Our study indicated that rice-upland crop rotations were the most useful systems for sustainable rice production in the Mekong Delta. Although, the research objectives of this dissertation were met, several aspects still need further research.

From the results presented, it became clear that rotation of rice and upland crop with preparation of beds and thus loosening of subsoil improved soil quality and significantly affected rice yield in the long-term. However, in this study, the potential additional effect of the crops per se (maize and/or mung bean as compared to rice) could not be deduced from the experimental design. We could not indentify the separate contribution of the improving factors (mechanical soil loosening and plant impact). In further research a treatment with “mechanical soil loosening only, without plants” and “upland crop cultivation only, without soil loosening” could therefore be included.

The variation of soil properties that was observed with depth suggests that in future related research, samples should be taken at different layers of 10 cm increments. Sampling at those depths is needed for differentiating cropping system effects.

Though promising, crop rotations of rice and other crops is only one way to maintain soil quality. Alternatives such as use of organic fertilizer (e.g. straw compost) on soil properties and crop growth should be tested. This could reduce the need for chemical fertilizer without decreasing the yield of rice crop and may alleviate the environmental impacts.

Recent studies also showed that biochar is effective to mitigate climate change through increasing carbon storage while decreasing direct greenhouse gas emissions, improving soil quality and crop productivity. This should get more attention in the upcoming years, especially in the paddy soil in the Mekong Delta.

Although rotations of rice with upland crops showed the best results in terms of soil quality, yield and income, their impact on greenhouse gas emissions (CH_4, NO_2 and CO_2) should be investigated. As the rotations affect the moisture regime in the soil with soils being subjected to anaerobic and aerobic conditions, they will surely affect those emissions. It must therefore be investigated to what extend those cropping systems contribute to or mitigate global change by reduced or increased emissions of specific greenhouse gases.

As the area is coping with floods and droughts, and to reduce the pressure on water resources, appropriate water use management strategies based on improved root-zone water balance studies should be worked out.

Yet, although macronutrient management is typically the initial driving force of rice yield in the long term, deficiencies of micronutrients are also important constraints to sustaining high yield levels. In addition, Fe toxicity could be an additional constraint to rice crop growth. Further research would be necessary to investigate the effect of micronutrient fertilizers and Fe toxicity on rice growth and yield.

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1

Appendices

A. Individual soil horizon description and soil profile picture

- Date of soil profile description: 23/7/2003.
- Authors: Tran Ba Linh and Le Van Khoa

Ap: 0 – 20 cm

Distinguished by root distribution

Very dark grayish brown (10YR 3/2) moist, gray (10YR 5/1) dry; clay; many yellowish brown (10YR 5/6) spots; massive; slightly sticky and plastic; ripe; few open, tubular, biopores (0.5 – 1.0 mm); many brown fresh fine roots; 10-15% half decomposed organic matter, few spots of dark decomposed organic matter mixed in the soil matrix; clear, boundary to:

AB: 20 – 55 cm

Recognised by soil matrix colour and soil mottling pattern

Black (5Y 2.5/1) moist, gray (2.5Y 5/1) dry; clay; 5-10 % brownish orange (2.5YR 3/6) and brown (7.5YR 4/4) distinct, clear fine mottles distributed mainly in soil matrix; massive; sticky and plastic; rip; clear, boundary to:

Bg1: 55 – 75 cm

Distinguished by soil matrix color and soil structure

Gray (2.5Y 5/1) moist, light gray (2.5Y 7/1) dry; clay; 15-20 % strong brown (7.5YR 5/6) distinct, clear fine mottles distributed mainly in soil matrix; weak, coarse subangular blocky; sticky and plastic; ripe; gradual, boundary to:

Bg2: 75 – 130 cm

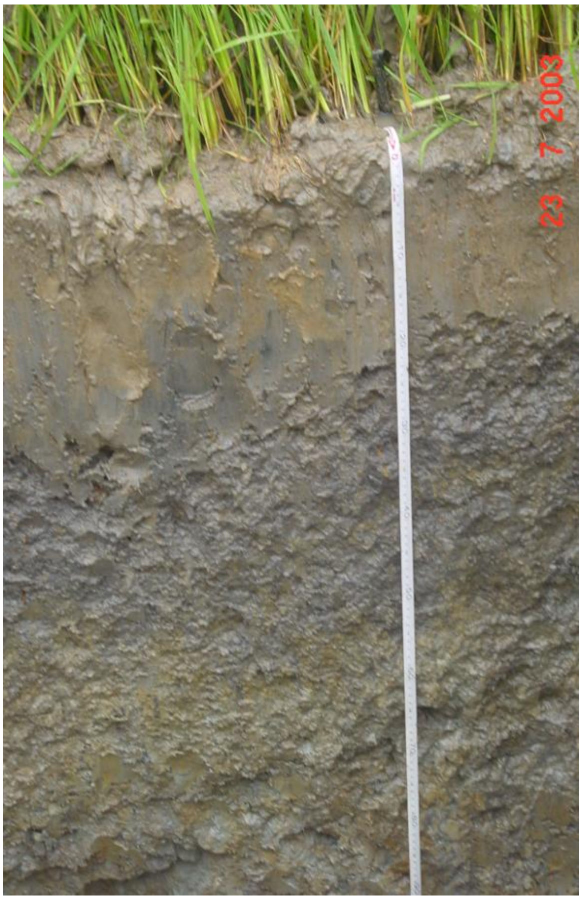
Justified by soil structure and mottling pattern

Gray (2.5Y 6/1) moist, light gray (5Y 7/1) dry; clay; 10-15 % reddish yellow (7.5YR 6/8), distinct, clear fine mottles irregularly mixed in 2-4 % dark yellowish brown (10YR 3/4) faint, disffuse mottles distributed mainly in soil matrix and on the surface of peds; weak, coarse prismatic; slightly sticky and plastic; nearly ripe; gradual, boundary to:

Cg: > 130 cm

Recognised by soil matrix color and soil material

Reddish gray (5YR 5/2) moist, light browish gray (10YR 6/2) dry; sandy loam; structureless; sticky and non- plastic; half ripe; common, soft, strong brown (7.5YR 3/4), fine angular, manganese nodules in soil matrix.



Soil profile picture in study location

B. Interview sheets

B.1 History and present cropping system at Cai Lay district - Tien Giang province Mekong Delta-Vietnam

1. **Sheet number**……………………..**Date of interview:**……………………

2. **Location:** Community:……………………….Village..…………………..

3. **Farmer information:**

Full name:…………………………………………..Age:………………

Address: ....

Time of settlement and cultivate:........ ....

Name of cropping system:…………………………………………….

Field area: .... ha, in which:

Rice:………………ha. Upland crop rotation with rice: ....ha

4. General history of study location

4.1 What was land use before the field was turned to agriculture production:...…...

4.2 For agriculture purpose from year:………………………………………

4.3 Crop season schedule: Draw crop season schedule within year:

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

4.4 Field status: compaction, declining soil fertility, lack of water in dry season.

Other:……………………………………………………………………...

5. Soil preparation methods

By machinery plow:……………from year :……………..to year………..

By small handle tractor:………….from year :……………..to year………

Types:……………………………………………………………………

Soil moisture when using machine (dry, moist, wet):………………………….

Depth of tillage (cm from soil surface):………………………………………

Time, season, how many times/year?..

Preparation of raised bed for upland crops (how to do, which equipment, depth in cm from soil surface)?

....

....

6. Crop variety and seed amount for planting practice:

Rice 1:…………………..….Reason why chosen………………………………

Rice 2:…………………..….Reason why chosen………………………………

Rice 3:…………………..….Reason why chosen………………………………

Upland crop 1:……………Reason why chosen…………………………......

Upland crop 2:……………Reason why chosen…………………………......

Upland crop 3:……………Reason why chosen…………………………......

7. Fertilizers for field: Total amount/crop:

Type	Crop 1	Crop 2	Crop 3

Method of fertilizer application………………………………………………

Dose of fertilizer in present and past: different or not? If different, why?

…………………………………………………………………………………

8. Plant protection: insecticide and pesticide

Type	Crop 1	Crop 2	Crop 3

Other types (if any):…………………………………………………………

9. Crop residue management:

Rice:…………………………………………………………………………….

Upland crop………………………………………………………………

10. Capital input for all of activities during the crop cycle

No	Activities	Crop 1	Crop 2	Crop 3
1	Seeds			
2	Soil preparation			
3	Fertilizers			
4	Pesticides			
5	Labor			
6	Irrigation			
7	Harvest			
8	Other (if any)			
9	Total input			
10	Total income			
11	Total profit			

11. Hydrology status

11.1 Flooding time

Start:…………………………………End:…………………………………

Flooding depth (cm):……………………………………………………..

Cause of flooding:………………………………………………………..

11.2 Irrigation capacity

Nature or pump:…………………………………………………………

Enough irrigation water for whole year:…………………………………..

If not, which season? ......…………………………………………………

How to improve?...

11.3 Rainy season

Start:..............................End…………………………………………..

Time (month) of highest rain amount:……………………………………

Comment about the effect of climate on crop season, crop yield:

………...........................………..

12. Selling farm produces:

…………………………………………………………………………

…………………………………………………………………………

13. Main limit factors effected to agriculture cultivation

No	Limit factors	Crop 1	Crop 2	Crop 3	Detail
1	Soil				
2	Water				
3	Crop				
4	Weather				
5	Insect and diseases				
6	Variety				
7	Lack of labor				
8	Price/sell				
9	Cultivation method				
10	Source of capital				
11	Costs of production				
12	Profit				
13	Lack of capital				
14	Other				

14. Plan to solve main limiting factors:

Soil:...

Water:...

Change cropping system present:...

Others:..

15. Comment on soil production:

……………………………………………………………………………………......................

....…........

....

16. Plan for soil management in the future:

……………………………………………………………………………………

……………………………………………………………………………………

…………………………………………………………………………………...

B.2 Rice yield evolution (within recent past 5 year)

Name of farmer:...

Address:..….

Name of cropping system:..

Field area (m^2):..

Rice yield (ton per area)	First year	Second year	Third year	Fourth year	Fifth year
Crop1:…………..					
Crop 2:………….					
Crop 3:………….					

Comment about the yield and reason why yield changed

Year 1:...

Year 2:...

Year 3:...

Year 4:...

Year 5:..

Curriculum Vitae

1. Personal information

- First name: LINH
- Family name: TRAN BA
- Place of birth: Dong Thap-Vietnam
- Date of birth: 13th February 1976
- Nationality: Vietnamese
- Email: tblinh@ctu.ed.vn, linh.tranba@ugent.be

2. Education

- 1994-1999: BSc. in Agronomy, Can Tho University, Vietnam.
- 2002-2004: MSc. in Physical Land Resources, Ghent University, Belgium.

3. Work experience

- From April 1999 to August 2002: Researcher of Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University, Vietnam.
- From September 2002 to September 2004: Master student in Physical Land Resources, option: Management at Ghent University, Belgium.
- From October 2004 to now: Lecturer and researcher of Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University, Vietnam.

4. Research activity

4.1 Journal Articles

International Journals with Peer Review

Linh, T.B., Sleutel, S., Guong, V.T., Khoa, L.V., Cornelis, W.M., 2015. Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture. Soil & Tillage Research 154: 44-52.

Linh TB, Sleutel S, Elsacker SV, Guong VT, Khoa LV, Cornelis WM. 2015. Inclusion of upland crops in rice-based rotations affects chemical properties of clay soil. Soil Use and Management 31: 313-320.

Linh, T.B., Khoa, L.V., Van Elsacker, S., Cornelis, W., 2016. Effect of cropping system on physical properties of clay soil under intensive rice cultivation. Land Degradation and Development 27: 973-982.

Linh, T.B., Cornelis, W., Sara, V.E., Khoa, L.V., 2013. Socio-economic evaluation on how crop rotations on clayed soils affect rice yield and farmers' income in the Mekong Delta, Vietnam. International Journal of Environmental and Rural Development 4-2: 62-68.

Takeshi Watanabe, Luu H. Man, Duong M. Vien, Vu T. Khang, Nguyen N. Ha, Tran B. Linh, Osamu Ito, 2009. Effects of continuous rice straw compost application on rice yield and soil properties in the Mekong Delta. Soil Science & Plant Nutrition Volume 55, Issue 6: 754-763.

Do Thi Thanh Ren, Tran Kim Tinh, Nguyen Thi Ngoc Minh, Tran Ba Linh, 2004. Applying mixed manure and inorganic phosphorus fertilizer to improve rice yield on acid sulphate soil (Hydraquentic Sulfaquept). Australian Journal of Soil Research 42: 693-698.

National Journals (in Vietnamese)

Võ Thị Gương, Trần Bá Linh, 2002. Effect of CropMaster fertilizer on rice yield in alluvial and acid sulphate soil in the Mekong Delta. Vietnam Soil Science Journal – Volume 16/2002 – ISSN 0868-3743. Vietnam Society of Soil Science.

Trần Bá Linh, Võ Thị Gương, Hồ Văn Hoàng, 2002. Effect of Agrostim fertilizer on rice yield in alluvial and acid sulphate soil in the Mekong Delta. Journal of Science Volume 3/2002. Can Tho University, Vietnam.

Trần Bá Linh, Lê Văn Khoa, 2006. Quantitative land evaluation for alternative crops with rice cultivation: Case study in Long Khanh Village – Tien Giang province. Vietnam Soil Science Journal – Special issue 2006 – ISSN 0868-3743. Vietnam Society of Soil Science.

Võ Thị Gương, Trần Bá Linh, 2008. Sustainable nutrient management in intensive rice cropping in the Mekong Delta. Selected Research Papers, Agronomy Department, Ministry of Agriculture and Rural Development, Vietnam.

Trần Bá Linh, Nguyễn Minh Phượng, Võ Thị Gương, 2008. The effect of organic fertilizer in improving soil bulk density and aggregate stability in the Mekong Delta. Journal of Science - Volume 10/2008 – ISSN 1859-2333. Can Tho University, Vietnam.

Trần Bá Linh, Nguyễn Mỹ Hoa, Võ Thị Gương, Huỳnh Thanh Ghi, 2009. Physical properties of peat soils at Vồ Dơi national reserve – U Minh Hạ - Cà Mau. Vietnam Soil Science Journal – Issue 31/2009. ISSN 0868-3743. Vietnam Society of Soil Science.

Nguyễn Mỹ Hoa, Trần Bá Linh, Võ Thị Gương, Huỳnh Thanh Ghi, 2009. Soil and water characteristics of peat swamp forest underlain by acis sulphate soil at Vồ Dơi national reserve, U Minh Hạ national park in the Mekong delta, Vietnam. Vietnam Soil Science Journal – Issue31/2009. ISSN 0868-3743. Vietnam Society of Soil Science.

Võ Thị Gương, Trần Bá Linh, Châu Thị Anh Thy, 2010. Improvement of soil fertility and rice yield in topsoil removal field in Chau Thanh district, Tra Vinh province. Journal of Science - Volume 16b/2010 – ISSN 1859-2333. Can Tho University, Vietnam.

Lê Văn Khoa, Trần Bá Linh, 2011. Possibility of cultivation of two rices and one cash crop in the rainfed area at Long Phu district – Soc Trang province. Journal of Science - Volume 18b/2011 – ISSN 1859-2333. Can Tho University, Vietnam.

4.2 Conference Contribution

International conference: oral presentation

2013: "Socio-economic evaluation on how crop rotations on clayey soils affect rice yield and farmers' income in the Mekong Delta, Vietnam" presented at the 4th International Conference of Environmental and Rural Development, Siem Reap, Cambodia 19-20 January 2013.

2014: "Temporal variability of soil physical properties under different land use types of clay soil in the Mekong Delta, Vietnam" presented at the 20th World Congress of Soil Science, Jeju, Korea, 8-13 June 2014.

International conference: poster presentation

2010: "Aerobic decomposition and organic amendment effects on grain yield of triple-cropped rice in the Mekong Delta, Vietnam" presented at the 19th World Congress of Soil Science, Brisbane, Australia, 1-6 August 2010.

2010: "Effect of crop rotation on soil quality and rice yield of silty clay soil in Mekong Delta, Vietnam" presented at the 3rd International Rice Congress, Hanoi, 8-12 November 2010.

2014: “Prospects of crop rotation for improving soil quality and rice yield in the Mekong Delta, Vietnam” presented at the 20th World Congress of Soil Science, Jeju, Korea, 8-13 June 2014.

2015: “Rice and soil relation under different rice based cropping systems in the Mekong Delta, Vietnam” presented at DesertLand II: Conference on Desertification and Land Degradation, Ghent, 16-17 June 2015.

2016: “Rice production in relation to soil quality under different rice-based cropping systems” presented at European Geosciences Union General Assembly, Vienna, Austria 17-22 April 2016

5. Tutor Master dissertations

Sara Van Elsacker (2011). Effects of land use and soil management on soil quality in the Mekong Delta, Vietnam” MSc. thesis. Ghent University, Belgium.

Titus Ghyselinck (2013). Temporal changes of physical soil properties under different land use systems and land management practices of alluvial soil in the Mekong Delta, Vietnam” MSc. thesis. Ghent University, Belgium.