Effects of land use and soil management on soil quality in the Mekong Delta, Vietnam

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Gent,

The Promoter, The Author,

Prof. dr. ir. W. Cornelis Sara Van Elsacker
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ABSTRACT

The Mekong Delta, situated in the South of Vietnam, is one of the biggest and most fertile deltas in South East Asia. Alluvial soils account for about 31.5 percent of the Mekong Delta, they have a silt-clay to clay texture and, because of the delta’s flat area, the soil is poorly drained. Low investment in diversification of crops, imbalanced fertilizer application, changing land use, and increasing mechanization have led to land degradation and consequently crop yield losses. This intensive land use also affects the farmers’ income.

A study area in Cai Lay district (Tien Giang province, belonging to the Mekong Delta), where the alluvial soils have been used intensively by many farmer generations, is representative for the current problems in the South of Vietnam. This area is suitable for rice production and therefore continuous rice cultivation is the dominant cropping pattern. The experimental site with different land use and land management practices was arranged in a randomized complete block design with four replications. Each plot has an area of exact 42 m². The six different treatments were: rice-rice-rice, rice-rice-rice+10 tons organic manure/crop season, rice-maize-rice, rice-maize (+10 tons organic manure)-rice, rice-mungbean-rice, rice-mungbean-maize. Physical and chemical soil quality indicators were determined to better understand and interpret sustainable management of the soil.

Results showed an improvement of soil quality for crop rotations with upland crops, particularly in the distribution of soil organic carbon, labile C and the nutrient supply. This was translated in a decreased bulk density, an increased total porosity and macro-porosity for the 20-30 cm horizon, which resulted in a higher air capacity, plant available water capacity, stability quotient and Dexter’s S-index. There was a high correlation (r=0.84) between soil organic carbon and water content at permanent wilting point, which implies that the water content at permanent wilting point was significant lower for the rotations with one upland crop. For matrix porosity, absence of optimum values made it difficult to interpret the results.

The addition of organic manure to the rotations (R-R-R+OM and R-M-R+OM) did not show a significant increase in soil organic carbon and labile C and subsequently, no difference in bulk density and total porosity was noticed. However, improvement in $N_{av}$, $P_{av}$ and total acidity has been observed in the rice monoculture and plastic limit, air capacity, stability quotient increased for both treatments with organic manure.
From the interviews with the farmers, it was concluded that the rice yield in the last five years increased when rotation with upland crops was implemented, which was strongly in contrast with the rice-yield decrease over the last five years for rice monoculture. Farmers are reluctant to use upland crops because of the higher (cost for) labor. We calculated, however, that the benefit/cost-ratio was the highest for rotation with one upland crop in between two rice cultivations.

SAMENVATTING

De Mekong Delta, gesitueerd in het zuiden van Vietnam, is één van de grootste en vruchtbaarste delta’s in Zuidoost Azië. Alluviale bodems nemen 31,5 procent van de Mekong Delta voor hun rekening en de bodems in deze omgeving hebben een lemig klei tot klei textuur. Doordat het gebied vlak is, is de bodem slecht gedradeerd en de weinige investeringen in gewasdiversificatie, onevenwichtige bemesting, veranderingen in landgebruik en stijgende mechanisatie hebben geleid tot landdegradatie en vervolgens tot daling van gewasopbrengst.

Een studiegebied in Cai Lay District (Provincie Tien Giang), waar alluviale bodems reeds vele generaties intensief door landbouwers worden gebruikt, is representatief voor de huidige problemen in het zuiden van Vietnam. Dit gebied is geschikt voor rijstproductie en daarom is continue rijstteelt de meest voorkomende landbouwactiviteit. Het proefterrein met verschillende grondgebruiken en landbeheer werd gerangschikt in een gerandomiseerd complete blok ontwerp met vier herhalingen. Elk stukje grond heeft een oppervlakte van 42 m². De verschillende behandelingen waren: rijst-rijst-rijst, rijst-rijst-rijst+10 ton organische mest/teeltseizoen, rijst-maïs-rijst, rijst-maïs(+10 ton organische mest)-rijst, rijst-mungboon-rijst en rijst-mungboon-maïs. Fysische en chemische bodemeigenschappen werden bepaald om een goed inzicht en een goede interpretatie van duurzaam bodembeheer te bekomen en om aan toekomstige behoeften te kunnen voldoen.

De resultaten toonden een verbetering in de verdeling van bodemorganisch materiaal, labiele koolstof en nutriëntaanbod bij gewasrotatie met maïs of mungboon. Dit werd vertaald in een verlaagde dichtheid, een verhoogde totale porositeit en macroporositeit voor de 20-30 cm horizon, wat resulteerde in een hogere luchtcapaciteit, hogere beschikbare watercapaciteit voor de plant, hogere stabiliteitsquotiënt en hogere Dexter’s S-index. Er bestond een hoge correlatie tussen bodemorganisch materiaal en het watergehalte bij permanent verwelkingspunt (r=0.84), wat inhoud dat de waterinhoud bij permanent verwelkingspunt voor rotatie met één niet-rijst
voedingsgewas lager was. De interpretatie van de matrix porositeit werd bemoeilijkt door de afwezigheid van optimale waarden.


Uit de interviews met de landbouwers kon worden geconcludeerd dat de rijstopbrengst de laatste vijf jaar een stijging vertoonde bij gewasrotatie met één of meerdere niet-rijst voedingsgewassen, wat sterk in contrast was met een zichtbare daling in rijstopbrengst bij monoculturen. Boeren zijn echter niet gewillig om niet-rijst voedingsgewassen te gebruiken door de extra (kost voor) arbeid. We berekenden echter dat de baten-kosten-verhouding het hoogst was voor de rotatie met één niet-rijst voedingsgewas tussenin twee rijstteeltten.
# TABLE OF CONTENTS

ACKNOWLEDGEMENT.................................................................................................................. i

ABSTRACT........................................................................................................................................ ii

SAMENVATTING.......................................................................................................................... iii

TABLE OF CONTENTS................................................................................................................... v

LIST OF FIGURES.......................................................................................................................... vii

LIST OF TABLES............................................................................................................................ viii

ABBREVIATIONS AND ACCRONYMS............................................................................................ ix

1. INTRODUCTION......................................................................................................................... 1

2. LITERATURE REVIEW.................................................................................................................. 3

2.1. Soil as a non-renewable natural resource...................................................................................... 3

2.2. Alluvial soils.............................................................................................................................. 3

2.3. Soil quality and soil health.......................................................................................................... 4

2.4. Soil degradation.......................................................................................................................... 8

2.4.1. Soil degradation processes.................................................................................................... 9

2.4.1.1. Loss of organic matter...................................................................................................... 9

2.4.1.2. Erosion............................................................................................................................ 9

2.4.1.3. Floods............................................................................................................................. 10

2.4.1.4. Salinisation and sodification.......................................................................................... 11

2.4.1.5. Compaction.................................................................................................................... 11

2.4.1.6. Contamination................................................................................................................ 12

2.4.1.7. Sealing............................................................................................................................ 12

2.4.2. Identification of soil degradation processes.......................................................................... 13

2.5. Restoration activities, land use and management...................................................................... 15

2.5.1. Soil sustainability and sustainable agriculture....................................................................... 15

2.5.2. Land evaluation.................................................................................................................... 15
LIST OF FIGURES

Figure 2.1: Multiple scales for soil quality evaluation (Karlen et al., 1997). --------------------------------- 8
Figure 3.1: Map of the Mekong Delta Vietnam, with the study location. ------------------------------ 19
Figure 3.2: Map of Tien Giang province, with the study location ---------------------------------- 20
Figure 3.3: Distribution of mean monthly rainfall and temperature at the experimental site. -------- 21
Figure 4.1: Bulk density for six different treatments, at three depths. ------------------------------- 35
Figure 4.2: Influence of six different crop rotations at three depths on soil matrix porosity. -------- 38
Figure 4.3: Influence of six different crop rotations, at three depths on the plastic limit, the liquid limit and the plasticity index. --------------------------------------------- 41
Figure 4.4: correlation between plastic limit and organic carbon. ---------------------------------- 42
Figure 4.5: Soil strength. -------------------------------------------------------------------------- 43
Figure 4.6: Air capacity of six different treatments at three depths. ------------------------------- 45
Figure 4.7: Effect of the treatments on soil water retention characteristics, at depth 0-10 cm. ---- 48
Figure 4.8: Effect of the treatments on soil water retention characteristics, at depth 10-20 cm. ---- 48
Figure 4.9: Effect of the treatments on soil water retention characteristics, at depth 20-30 cm. ---- 49
Figure 4.10: Rice yield within recent past 5 years (kg/ha) for different land management systems. --- 56
Figure 4.11: Cost and income for different crop rotations. ----------------------------------------- 57
LIST OF TABLES

Table 2.1: Summary of soil characteristics and soil-forming factors that determine soil degradation processes. .......................................................................................................................... 13

Table 3.1: Nutritional characteristics of the compost used at the study location. ................................. 22

Table 4.1: Chemical properties: EC, CEC, SOC, labile C. ................................................................. 31

Table 4.2: Chemical properties: TA, N_{av}, P_{av}. ............................................................................. 33

Table 4.3: Particle density, total porosity and clay content for the six different treatments. .............. 36

Table 4.4: Influence of six different crop rotations at three depths on soil macro-porosity ................. 40

Table 4.5: Influence of six different rotations of crops at three depths on selected soil physical quality indicators and parameters. ............................................................................ 46

Table 4.6: Soil water characteristics for six different crop rotations at three depths. ......................... 51

Table 4.7: Mean area under cultivation (ha) and costs-benefit ratio. .................................................. 58
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Air Capacity</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
</tr>
<tr>
<td>CEC</td>
<td>Cation Exchange Capacity</td>
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<tr>
<td>EC</td>
<td>Electric Conductivity</td>
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<td>FA</td>
<td>Factor Analysis</td>
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<tr>
<td>FAO</td>
<td>Food and Agriculture Organization</td>
</tr>
<tr>
<td>FC</td>
<td>Field Capacity</td>
</tr>
<tr>
<td>IS</td>
<td>Instability Index</td>
</tr>
<tr>
<td>Ks</td>
<td>Saturated hydraulic conductivity</td>
</tr>
<tr>
<td>LL</td>
<td>Liquid Limit</td>
</tr>
<tr>
<td>MacPOR</td>
<td>Macro-porosity</td>
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<tr>
<td>MatPOR</td>
<td>Matrix porosity</td>
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<tr>
<td>MBC</td>
<td>Microbial Biomass Carbon</td>
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<tr>
<td>MDS</td>
<td>Minimum Data Set</td>
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<tr>
<td>P</td>
<td>Precipitation</td>
</tr>
<tr>
<td>PAWC</td>
<td>Plant Available Water Capacity</td>
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<tr>
<td>PI</td>
<td>Plasticity Index</td>
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<td>PL</td>
<td>Plastic Limit</td>
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<tr>
<td>RH</td>
<td>Relative Humidity</td>
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<tr>
<td>RWC</td>
<td>Relative Water Capacity</td>
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<td>SI</td>
<td>Stability Index</td>
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<tr>
<td>SQI</td>
<td>Soil Quality Index</td>
</tr>
<tr>
<td>SOC</td>
<td>Soil Organic Carbon</td>
</tr>
<tr>
<td>SOM</td>
<td>Soil Organic Matter</td>
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<tr>
<td>SSSA</td>
<td>Soil Science Society of America</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>TA</td>
<td>Total acidity</td>
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<tr>
<td>TAW</td>
<td>Total Available Water</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
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1. INTRODUCTION

Vietnam is a country in South East Asia with 84,967,524 inhabitants. Since 2000, there has been a strong progress in the agricultural sector in Vietnam, with an overall growth of 4 percent a year. Vietnam is the world’s second large rice exporter and the livelihoods of 90 percent of the poor inhabitants, or two thirds of the population, of Vietnam are dependent on agriculture (Worldbank, 2010).

The Mekong Delta, situated in the South of Vietnam, is one of the biggest and most fertile deltas in South East Asia. This region provides 50 percent of Vietnam’s rice production, 90 percent of the rice export volume and 70 percent of the fruit production output (Vietnam Business Forum, 2010). Water from the Mekong River is used for irrigation, fishing and domestic use and is the main water resource (Minh, 2000).

Soil groups of alluvial sedimentation account for about 31.5 percent of the Mekong Delta and are generally located on the river side. The soils in these surroundings have a silt-clay to clay texture and, because of its flat surface, the soil is poorly drained.

Low investment in diversification of crops, imbalanced fertilizer application, changing land use, and increasing mechanization have led to land degradation and consequently crop yield losses. This intensive land use also affects the farmer’s income.

As a result of sea level rise and intensive rice-shrimp farming, intrusion of saltwater occurs. Sustainable management of the soil is necessary because it is a non-renewable resource and thus needs protection to ensure the fulfillment of future needs. Good understanding and interpretation of possible soil quality indicators is important to meet this goal. The objective of this research was therefore to assess the impact of land management practices on soil quality.

A study area in Cai Lay district (Tien Giang province, belonging to the Mekong Delta), where the alluvial soils have been used intensively by many farmer generations, is representative for the current problems in the South of Vietnam. This area is suitable for rice production and therefore continuous rice cultivation is the dominant cropping pattern. This intensive land use involves the growth of three rice crops per year, and even up to seven rice crops in two years. Over several years many different farming practices, such as irrigation, drainage, tillage under wet soil conditions, inorganic fertilizer application, pesticide use and burning of plant residues, have been implemented. This poor land management and intensive farming are some of the causes of the land degradation. The local farmers in this area observed that rice yield has been gradually
Chapter 1: Introduction

declining every year, even when the same amount (or even an increasing amount) of chemical fertilizer was applied. Experiments have been set up to understand how to avoid these negative effects. They comprise new land utilization systems that exist of rotation of rice and upland crops in order to improve soil fertility and hereby farmer’s income.

Important soil properties for evaluating soil change and soil quality in agricultural systems, particularly on alluvial soils in the Mekong Delta, were determined to provide a clear evaluation and better understanding of the effects of land use and soil management practices on soil quality, in general.

The main questions that have been addressed were:

- Are soil characteristics related to soil degradation?
- Is there a relationship between soil quality and the present and historical land uses and land management practices?
- How can we control and restore soil degradation in alluvial soils in the Mekong Delta?
- Based on the obtained data, can we identify soil quality in the future for the studied soil group as well as introduce new land use systems and land management practices?
2. LITERATURE REVIEW

2.1. Soil as a non-renewable natural resource

Soil is a natural resource with crucial ecological, economic and social functions. It is the upper part of the earth crust that exists of mineral and organic solids, and pores filled with air and water. Soil is the essential component of the terrestrial environment and forms the interface between geosphere, atmosphere, hydrosphere and biosphere (Doran and Parkin, 1994).

The proportions of different components, especially sand, loam and clay, organic matter, mineral components, water and air (especially in the pore space) and the way they form a stable structure, determine the soil characteristics. Every soil exists of different horizons, with different physical, chemical and biological properties. Chemical properties are mostly related to the clay fraction and soil organic carbon, while physical properties are determined by the size distribution of the mineral particles (Wild, 2003).

This non-renewable resource has several important functions, including: biomass production; storing, filtering and transforming nutrients and water; hosting the biodiversity pool; acting as a platform for most anthropogenic activities; providing raw materials; acting as a carbon pool and storing geological and archeological heritages. These functions are determined by the soil characteristics and makes it important to understand the physical, chemical and biological processes and their interactions (Hassett and Banwart, 1992; Tóth et al., 2007).

Soil structure and characteristics are the result of soil formation. Most important factors of soil formation are parent material, relief, climate, time, biological and anthropological factors. Soil is known as a non-renewable resource because formation and recovery are time-consuming (MIRA, 2007).

2.2. Alluvial soils

Alluvial soils are relatively young (less developed) soils in alluvial plains (Edelman and Van der Voorde, 1963). They are deposited by water and origin from the youngest geological time period, the Holocene (Brady, 1990). These soils are worldwide responsible for more than 25 percent of the food supply.

The properties of alluvial soils vary strongly and are dependent on the mineral composition, the origin of the sedimentary material and deposition of the soil. In the Mekong river, because of its excessive basins, supplied sediment is rich in nutrients. Unlike in moderate climates, deposits in
the tropics contain little CaCO$_3$. This makes tropical alluvial soils often acid and subjective to faster degradation of organic material, what in general implies a low organic carbon content for these soils (Edelman and Van der Voorde, 1963).

The fertility of alluvial soils is dependent on the type of deposited clay mineral. In the tropics the most important clay minerals are kaolinite, illite (by contact with seawater) and montmorillonite. The physical fertility of alluvial soils mostly depends on the structure and its swell and shrink capacity (Brady, 1990).

The Mekong Delta is occupied by one million ha of alluvial soils (Khoa, 2002), this is 31.5% of the delta’s land area (Chieu et al., 1990; Ve and Anh, 1990). The Mekong river transports every year 500 milliard m$^3$ water, containing 70 million tons of sludge. Sedimentation occurs every year during the flood season in the delta area. Agronomically, the alluvial soils are the best soils in the Mekong Delta. The pH varies from 4.5 to 6.5. The topsoil exists of 2 to 5% organic material, but this declines strongly with the depth (C/N for topsoil: 5-12; C/N for lower horizons: 12). Total nitrogen is moderate for the topsoil (0.1-0.3%), but much lower for underlying horizons (to 0.05%). The phosphorus concentration also declines with the depth (from 0.08% to lower than 0.05%). The total content of potassium is generally high (0.10-0.15%) (Cartrysse, 1999).

### 2.3. Soil quality and soil health

#### 2.3.1. Soil Quality

According to the Soil Science Society of America (SSSA) the simplest definition of soil quality is “the capacity of soil to function”. A more extended definition represents soil quality as: "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997).

Soil quality can be seen in several different ways. In the past it was seen in relation to plant cultivation and crop productivity, resulting from physical, chemical and biological soil fertility. Fertility indicators were soil-water-air ratio in the soil, formation of soil aggregates, water-holding capacity, rooting, potential of nutrient supply, adsorption capacity of nutrients and abundance of soil organisms (MIRA, 2007).

Doran et al. (1996) recommend that soil quality rather should be based on its soil function. If a soil is not suitable for a specific use, it should not be used to define soil quality for this specific use. Most of the time it is not possible to make a perfect combination between soil and its
intended function, which makes that use of a best management scenario is recommended. The functions, processes and attributes of ecosystem concepts and indicators are a useful framework to indicate soil quality. Soil quality defines an objective state or condition of the soil, but also has to be seen subjective because evaluation is dependent on personal and social determination (Carter, 2002). An agricultural soil with good quality promotes and sustains good agricultural productivity with a negligible environmental impact and possesses physical, chemical and biological attributes to fulfill these requirements (Reynolds et al., 2007).

Soil quality can be subdivided in his inherent capacity for crop growth and in a dynamic part, influenced by its user. Dynamic soil quality contains the soil properties that change in a short time period and that are influenced by human activity, i.e. agronomic practices. This assumes that when the soil operates at its full potential for a specific land use, optimal quality is achieved (Karlen et al., 1997). Inherent soil quality encompasses soil’s natural composition, function of soil state factors and geological materials. The typical characteristics are almost static and change little over time, like mineralogy and particle size distribution. One should also consider extrinsic factors such as climatic, topographic and hydrologic parameters to evaluate inherent soil quality for crop production. For example, retention of moisture in clay soils is favorable for semiarid areas but is undesirable for humid conditions in poor drained areas. This makes that no universal set of inherent soil criteria exists (Carter, 2002) and implies that if ecosystem processes are well understood, the system will be truly sustainable (Karlen et al., 1997; Carter, 2002). Ecosystem management and soil interpretation can be improved by evaluation of the relationship between inherent and dynamic properties (Levi et al., 2009).

It is also possible to divide soil quality in soil physical, soil chemical and soil biological quality, although these components interact and thus are not truly separable (Reynolds et al., 2007).

In general, sustainable land use is very important for agriculture and forestry to guaranty a good soil quality. Sustainable soil use is referred to “the use of soils as a natural resource on a way that does not exert any negative effects - that are irreparable under rational conditions - either on the soil itself or any other systems of the environment” (after Tóth et al., 2007). Sustainable methods of land management can guarantee good soil use if the material and energy flows associated with soil processes are controlled and positively influenced. This means that a good soil quality eventually can be preserved by good management and maintenance of soil characteristics.
Farming needs simple and affordable measurements to compare and control options for land use and to measure the risk of soil degradation caused by their management practices. Soil quality assessment can serve as a basis for this comparison and is the main criterion for planning and practicing sustainable soil use.

### 2.3.2. Soil Heath

Doran and Zeiss (2000) defined soil health as: “the continued capacity of soil to function as a vital living system, by recognizing that it contains the biological elements that are the key to ecosystem function within land use boundaries”. A healthy soil has to be able to sustain biological productivity, maintain the quality of surrounding air and water and to promote animal, plant and human health (Doran et al., 1996). Most of the time, the terms soil quality and soil health are used interchangeably, but it is important to notice that soil quality is linked to its function and that soil health presents soil as a dynamic, living and finite non-renewable resource (Doran and Zeiss, 2000).

### 2.3.3. Soil Quality Indicators

Certain parameters or indicators can measure the overall soil quality. A group of chemical, physical and biological indicators can form a minimal data set (MDS), which can be measured at regular intervals and be compared with predefined standards. These indicators meet the demand for evaluation of the effect of management on soil function (Doran and Parkin, 1994). A MDS is depends on the land use and the site (Baldwin, 2006).

Parameters of the MDS are sensitive to management changes and change should be detected in relative short time. The data and measurement methodology should be accessible to most people and the parameters for the MDS should have a utility in defining ecosystem processes (Doran, 2002). Standardized methodology and threshold values for interpretation of soil quality indicators is utterly important (Doran and Parkin, 1994). The MDS provides a list of indicators necessary for assessment of soil quality (Doran and Parkin, 1996).

### 2.3.4. Soil Quality Evaluation

To evaluate soil quality, a conceptual framework could be used (Figure 2.1; Karlen et al., 1997). This scheme recognizes that soil quality can be seen as an inherent or a dynamic function and can be evaluated at different scales.

The first questions to be asked in the scheme are: how does the soil work and which indicators can be used to make an appropriate evaluation? The second step is to develop parameter values to indicate on which capacity a system is working. After this, a point-scale evaluation of soil
quality of sub-disciplinary levels can be made. This means that soil function can be assessed in terms of physical, chemical and biological properties and processes. Physical parameters (e.g. soil structure, pore space size and distribution, aggregate stability, saturated hydraulic conductivity, particle bonding or retention mechanisms) might be used to evaluate how well a certain soil accepts, retains and transmits water to crops. Chemical parameters include exchange capacity, pH, C-content and absorption capacity. Biological properties of soil quality to sustain plant growth include microbial biomass, respiration, mycorrhizal associations, nematode communities, enzymes or fatty-acid profiles as parameters. The framework somehow influences the function for which the assessment was made, needs some definable standards to compare with and has to be sensitive enough to observe differences between time and space in the point-scale. The point-scale can be extrapolated to develop full-potential values for soil groups. Plot-scale can be directed with a disciplinary focus (level 1), but cross-disciplinary is more useful for larger systems (level 2).

The evaluation of soil quality leads from an experimental mode, that helps to understand the mechanisms and processes, to a monitoring approach (level 3). This implies that land managers and decision makers have to cooperate with researchers to use existing information and identify knowledge gaps. In the last level (level 4) the need for regional, national and international assessment of soil quality is identified. This level uses very broad general perspectives for overall soil quality and sustainable land use (Karlen et al., 1997).

However, to evaluate land management in the near or distant future, this soil quality evaluation is not sufficient. To monitor changes in sustainability and environmental quality, to identify production problem areas, a soil quality index, which integrates different indicators, should be used (Doran and Parkin, 1994).
2.4. Soil degradation

Soil degradation can be defined as the loss of soil or soil quality for a number of soil functions. Loss of organic matter, erosion, floods, salinisation, compaction, landslides, contamination and sealing are the eight most important degradation processes and are closely related to agriculture. Most of the degradation processes are strongly correlated. Risk of soil degradation can also be caused by extreme natural condition, but are rather rare in comparison with human influence (Blum, 1998).

Degradation of soil has a direct impact on water and soil quality, influences food chains, climate change and hinders biosphere functioning (Tóth et al., 2007). This makes it important to
maintain a good soil condition to guarantee good environmental conditions and high productivity (MIRA, 2007).

2.4.1. Soil degradation processes

2.4.1.1. Loss of organic matter

The most important function of organic matter is to supply the binding and buffer capacity of the soil and contributes to limit diffusion of contaminated water through the soil (MIRA, 2007). Soil Organic Matter (SOM) provides the sequestration of atmospheric CO$_2$ and emits some greenhouse gasses. Change in land use can elevate CO$_2$- and greenhouse gas emission (Batjes, 1996). Soil Organic Carbon (SOC) is one of the most important components of SOM. SOC is indispensable for ecosystem functioning, has a major influence on soil structure, water holding capacity, cation exchange capacity (CEC) and soils’ ability to form complexes with metal ions and nutrients for storage (Milne et al., 2007). Moreover, soil is very important for the global carbon cycle (MIRA, 2007).

The decline of SOM is mainly caused by climate change, decoupling of cattle breeding and agricultural activities and of intensification of agricultural practice, e.g. higher frequencies and depth of tillage, continuous cropping and narrow crop rotations (Gardi et al., 2008). In agriculture, the factors to be controlled to reduce SOM-loss are crop rotation, tillage and management practice (Rickman et al., 2002). Loss of SOC can cause shortage of nutrients for sustainable plant production (Maréchal et al., 2008).

To restore SOM content in crop cultivation, land management options such as improved farming on eroded soils, reduced or no tillage, improved residue management, organic amendment, and improved crop rotation should be introduced (Dawson and Smith, 2007).

Loss of SOM often depends on other degradation processes like wind and water erosion, floods and landslides (Dawson and Smith, 2007).

2.4.1.2. Erosion

Soil erosion is the detachment, transport and deposition of soil particles. It can be divided in wind- and water erosion and mass movement. Erosion caused by operation processes is also seen as a separate process and occurs as soil displacement due to tillage and is termed “tillage erosion” (Wildemeersch et al., 2011).
Chapter 2: Literature review

Water erosion is a natural process caused by loss of organic matter content, topography, type and amount of vegetation covering the soil and by intensive rainfall. However, it can be increased drastically by human activities (e.g. crop practice, deforestation,...) (Gay et al., 2009).

Erosion of cultivated soils frequently results from aggregate breakdown (i.e. slaking, breakdown by differential swelling, mechanical aggregate destruction by rain drop impact and physico-chemical dispersion) and its relative importance depends on the nature of the rain and soil’s physical and chemical properties. Soil’s susceptibility to this kind of erosion can be expressed by its aggregate stability (Le Bissonnais, 1996).

Wind erosion has a major influence on fine particles and results, among others, in fertility degradation and reduction of air quality. This makes that the effects of wind erosion on agricultural productivity are only observed after a long time. Other interactions of various factors, such as land use, have a large influence on wind erosion risk (Gay et al., 2009).

Tillage erosion is caused by agricultural tools and plowing is the main process that provides vertical and lateral displacement of soil. This phenomena leads to redistribution of nutrients and organic matter, which can cause that there are relative impoverished zones and other zones with accumulation of too much nutrients (MIRA, 2007).

Finally, export of soil during harvesting of crops is an important factor of erosion, especially when the harvested part is located under the ground. This leads to reduction of soil quality and sequentially to reduced crop yield (Gay et al., 2009).

2.4.1.3. Floods

Flooding is strongly correlated with erosion and compaction (Gay et al., 2009). In urban areas this effect is mainly caused by replacing the vegetated soil by impermeable surfaces or bypassing the natural storage (Wheater and Evans, 2009). In agricultural land use, flooding is not always negative. It has an important influence on the grade of soil salinisation (Tóth et al., 2008).

The Mekong Delta is subjected to flooding half of the year (1.2-1.8 million ha). This causes loss of lives and property but is also beneficial because salty and acid water is washed away and deposits of sediment provides fertilization to the soil (Hoa et al., 2008). The rainy season starts in May and during this period farmers plough their soil for rice cultivation. A large amount of toxis are released by the ploughing and need to be flushed out by the floods.
2.4.1.4. **Salinisation and sodification**

Salinisation can be defined as a process that leads to an excessive amount of water-soluble salts in the soil (Várallyay and Tóth, 2006). High amounts of sodium ions in the soil or on the cation exchange sites result in sodification. Primary salinisation is the accumulation of salts through natural processes, e.g. high salt content in parent material or groundwater. Salinisation caused by human activities, such as irrigation with salt rich water or insufficient drainage is grouped as secondary salinisation (Qadir et al., 2008).

Excessive salt intrusion in agricultural soils causes decreasing yields or even crop failure. These adverse effects are especially caused by the osmotic stress due to the presence of excessive salts and by toxicity or deficiency of certain nutrients (Qadir et al., 2008).

This threat cannot be reduced with time by routine irrigation and crop management practices but needs soil amelioration. Amelioration includes movement of excess soluble salts deeper in the soil via leaching or biological reduction of the salt in the soil by extraction with salt accumulating plants (Qadir et al., 2000).

Currently, 42 percent of the Mekong Delta is affected by salinity intrusion. This serves as the limiting factor for agricultural production and causes shortage of drinking water for the local population (Minh, 2000).

2.4.1.5. **Compaction**

Soil compaction is a human induced problem (FAO, 2003) and is caused by compressive sources on the soil, e.g. passage of tillage implemented in agricultural areas (Le Bas et al., 2006). Orientation, size and shape of soil aggregates, increase in bulk density and reduction of porosity indicates soil compaction (Gardi et al., 2008). Clay soils are most susceptible to this degradation (Gay et al., 2009). The created damage depends on the water content and the bearing capacity of the soil and the magnitude of the pressure force applied. The compaction mostly occurs at the surface but to which depth the forces are transmitted depends also on the moisture content (Batey, 2009).

Compaction strengthens the erosion effects and can lead to crop failure due to negative effect on the crop root depth, water availability and poor aeration of the soil (FAO, 2003).

To avoid this soil threat, the time of tillage is important because the degree of compaction depends on the soil moisture content (Batey, 2009). No-tillage agriculture is the best alternative (Le Bas et al., 2006). Soil compaction can be restored using rotation crops with natural crop-
induced wetting and drying cycles to crack the soil, crops that provide root penetration and increase the organic matter in the soil (FAO, 2003).

2.4.1.6. Contamination
Soil contamination is defined as the occurrence of certain products in such a concentration that it causes deterioration or loss of soil functions. The most common contaminations are heavy metals and high levels of nitrogen. High nitrate and phosphor concentrations introduced by fertilizers and manure are the most common diffuse contaminants in agricultural soils (Gay et al., 2009).

These contaminations reduce the capability to serve nutrients to crops, to buffer and filter. Consequently, this leads to yield reduction, leaching of nutrients to groundwater and eutrophication (Maréchal et al., 2008).

In agriculture, soil contamination remediation is rarely used because the cost is too high. Crop rotation contributes to reduction of the use of chemicals and thus reduces contamination. Some plants absorb contaminants and thus improve water and soil quality. Biological activity also has a positive influence on the grade of contamination because it stimulates the breakdown of chemical components (Gay et al., 2009).

In the Mekong Delta a large amount of inorganic fertilizers are used and is stimulated by the government with price incentives. This causes high amounts of nitrogen with as consequence a high population of brown plant hoppers and other pests. The wrong use of fertilizers also brings farmer and consumer at risk (Dung et al., 2000).

2.4.1.7. Sealing
It should first be noted that there are two definitions of sealing. In the Thematic Strategy on Soil Protection it is defined as: “Soil sealing is the separation of soils from other compartments of the ecosystem, such as biosphere, atmosphere, hydrosphere, anthroposphere and other parts of pedosphere by layers and other bodies of completely or partly impermeable material”. The second definition, that will be used in the context of this study, is: “Soil sealing is the changing of its nature so that the soil becomes impermeable, such that soil is no longer able to perform the range of functions associated with it” (Van Camp et al., 2004).

The extend of sealing is affected by the texture of the soil (Segeren and Trout, 1991). Soils with a high aggregate stability are more resistant to surface sealing (Maréchal et al., 2008). This aggregate stability highly depends on the organic matter content and the initial humidity of the soil (Singer and Le Bissonnais, 1998) and is affected by raindrops or chemical dispersion. Soil
sealing enhances erosion and run-off (Thierfelder et al., 2005) and causes infiltration reduction of water (Singer and Le Bissonnais, 1998).

A minimum tillage method and crop rotation improve the physical soil status and reduce the susceptibility to sealing (Thierfelder et al., 2005).

2.4.2. Identification of soil degradation processes

Table 2.1 lists several soil characteristics and soil forming factors that determine soil degradation processes. The table indicates potential influence of the external factors of degradation on the soil response properties, while the actual degradation is site-specific.

The influence of soil texture on organic matter decline depends largely on the type of soil. Sandy soils usually have already a low SOC content while clay soil mostly accumulate humus. Aggregate stability (and soil structure) is also closely related to SOC and these two factors strongly influence soil biodiversity.

Soil-forming factors are natural and anthropogenic processes. Soil degradation can be accelerated or slowed down by human activities. An actual example is that climate change will influence all soil degradation processes. Climate influences water holding capacity and this has a large effect on other soil properties. The water balance in the soil is important for salinisation, temperature and precipitation influence carbon mineralization and accumulation (Gay et al., 2009).
Table 2.1: Summary of soil characteristics and soil-forming factors that determine soil degradation processes (after Gay et al., 2009).

<table>
<thead>
<tr>
<th>Soil degradation processes</th>
<th>Water erosion</th>
<th>Wind erosion</th>
<th>Tillage erosion</th>
<th>Organic carbon decline</th>
<th>Compaction</th>
<th>Salinisation/sodicification</th>
<th>Contamination</th>
<th>Soil biodiversity decline</th>
<th>Landslides and floods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Texture</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Porosity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Infiltration rate/capacity</td>
<td>X</td>
<td>(X)</td>
<td>(X)</td>
<td>X</td>
<td>(X)</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Gas permeability</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aggregate stability (size)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Moisture content/holding capacity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Soil temperature</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Chemical</td>
<td>X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>pH/acidity/alkalinity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Organic carbon</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>N (cycle)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>P (cycle)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>K (cycle)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Electrical conductivity (EC)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Biological activity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Parent material and substratum</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Climate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Landform and topography</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Hydrology and soil moisture regime</td>
<td>(X)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Vegetation type/soil cover</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Human influences*</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Legend: X, essential factor in the process; (X), factor that has expectedly an influence on the process; empty field, no particular known influence; *, Human influence here often refers to (change of) land use. However, other farming practices such as stocking density, cultivation techniques or field size can also play a role.
Chapter 2: Literature review

2.5. Restoration activities, land use and management

2.5.1. Soil sustainability and sustainable agriculture

According to the World Commission on Environment and Development (1987), sustainability means to maintain or even improve environmental, technical, social and economic conditions for future generations. Sustainability becomes increasingly important when the scarcity of resources increases (FAO, 1993).

Sustainable agriculture includes productivity and economic, social and environmental components. Its key element is soil quality. Sustainable use depends on soil characteristics, related environmental conditions and land use. These three factors interact with each other: the change of one factor causes conversions in another. This makes sustainability of soil resources dynamic. Soil resources should be assessed from this point of view and can be seen as the prime object of sustainable land management (Tóth et al., 2007). Linking soil quality and degradation characteristics with time, is a primary indicator of sustainable management (Doran, 2002).

Scientific research on long-term sustainability of land management has a high priority to understand how soils respond to management and why certain soil-management systems are sustainable (Richter and Markewitz, 2001).

In agriculture, soil management is mostly seen as adding sufficient nutrients to maximize crop yield. However, this behavior has adverse environmental effects, e.g. large nutrient concentrations in water resources. Improvement of soil management includes the minimization of adverse on- and off-site effects, to become high productivity and high environmental quality (Richter and Markewitz, 2001).

2.5.2. Land evaluation

The assessment of land performance for a specific purpose is called land evaluation. In this evaluation economics, social (for the people surrounding the assessed area) and the consequences for the environment should be included (FAO, 1976).

Land evaluation can be performed by trial and error, empirical or by using process models. Trial and error is the least scientific way and has to be avoided. The empirical approach relies on the fact that result from an experiment can be transferred to similar situations. This method is only successful when the classification and identification of the land analogy has been chosen correctly. Process modeling is the best implementation for land evaluation because it recognizes the complex relationship between soil characteristics and land utilization. The models need
physical parameters as input. This method is only just starting to be used in soil survey and land evaluation (McKenzie et al., 2002).

Soil quality indicators (SQIs) can reflect the capacity of soil to function and are a measure for land evaluation. The development of these SQIs is essential to determine if soil quality under certain land uses is improving or declining. The integration of soil physical, chemical and biological properties and processes, the application under different field conditions, the complementation with existing databases or easily measurable data and their response to land use, management practices, climate and human factors is essential to develop SQIs. Linear and multiple regression analysis, pedotransfer functions, scoring functions and factor analysis (FA) are other techniques for identification or interpretation of SQIs (Shukla et al., 2006).

Multivariate data analysis of soil change and quality can contribute to a more holistic view on the effects of land use. With these techniques it is possible to develop a MDS with the parameters that are the most sensible to variation in land use and facilitates comparison among land use systems (Levi et al., 2009).

### 2.5.3. Impact of crop rotation and land use on soil quality

Crop rotation can improve soil characteristics and reduce pest pressure and consequently, yields will be higher and more stable (Liebman et al., 2001). The time of rotation and the combination of different crops will influence the soil physical parameters. This appears to be related to their different ability to promote soil structure formation and structure stabilization (Chan and Heenan, 1996).

Improvement of soil physical quality because of the implementation of crop rotation or different land management practice, can be measured by changes in parameters. The most important parameters are: organic carbon, Ks, bulk density, air capacity and relative water capacity (Reynolds et al., 2007).

According to a study on Alfisol soils in rain fed semi-arid tropics (Sharma et al., 2008) the most appropriate nutrient-management practice to improve soil quality is the use of organic fertilizer. In this study the organic matter caused a progress of 31.8% of the soil quality, over the control. The changes were most visible in microbial biomass carbon (MBC), available N and extractable Zn. In another study (Pagliai et al., 2004) the use of organic manure gives significant positive effects on soil structure, and thus soil quality improves. The use of manure or compost gives a higher macro-porosity value, due to less mineralization of SOM.
Rice is successful in crop rotation because of its indirect effects on environment and succeeding crops, and on the overall profit. Loss of surface elevation because of mineralization is reduced when rice is cultivated in tropical conditions. This favorable condition for rotation with vegetables is caused because of the higher water table in rice fields that doesn’t allow high oxygen concentrations in the soil which are necessary for mineralization. Another consequence of rotation with rice crops, called ‘rice effect’, improves the yield in crops that succeed rice in the rotation. This phenomenon could be possible explained because rice straw an stubble improve soil texture, improve drainage and store nutrients in an available form for the next crop. Rice cultivation has also some environmental benefits, e.g. improved water storage and removal of excessive nutrients in water runoff. In tropical climates water storage can be improved by use of rice crops because surface evaporation during the dry season is higher than evapotranspiration from the crop. Rice paddies are an excellent solution to high nutrient concentrations in drainage water. When the water is pumped into the rice fields, the algae and plants have enough time to consume these nutrients (Schueneman et al., 2008). Intensive rice monoculture is less favorable because of rapid nutrient depletion, soil compaction and its flooded conditions that destroy structure, porosity and reduce aeration (Verplancke, 2003).

Rotation between upland crops and rice with its flooded soils brings a transition in soil aeration status from anaerobic to aerobic and vice versa. This has impact on the accumulation and dissipation of soil mineral nitrogen, the PO$_4$-availability and K-exchangeability (George et al., 2002).

Plant roots cannot penetrate in very compacted soils, with a soil strength higher than 2,5 kPa. It is the hydrostatic (turgor) pressure in the roots that makes it possible to penetrate the soil. Some species, e.g. legumes (especially lupines) are able to grow in compacted soils and loosens compaction by their diurnal changes in root diameter. Rotation with these crops minimizes the risk on subsoil compaction and improves soil structure (Hamza and Anderson, 2005).

Because of the rapid population growth and the excellent environmental circumstances for rice cultivation, a lot of intensive rice-monoculture is used in farming in the Mekong Delta. It is generally known that the intensive use of the soil reduces gradually the rice-yield and increases need for agro-chemicals. The high doses of chemicals cause pollution of the water ways of rural areas and elevate the costs for the farmers. Diversification of crops could be a solution to these problems. In this study different crop rotations are considered and the results are measured with different SQIs.
2.6. Soil requirements of maize, mungbean and rice

A soil that is fertile provides enough water, nutrients, oxygen, an adequate rooting depth, a good temperature and no toxicities for the cultivated crops. The specification of these properties depends on the requirements of the crops. Farmers manipulate soil properties to achieve higher yield, but of course also climate and water applications play an important role (Wild, 2003). The requirements for maize, mungbean and rice as described in the next sections were taken from Sys et al. (1993).

2.6.1. Requirements of maize (Zea mays)

Maize is tolerant to a wide range of environmental conditions, but the growing season must be frost free. The optimum temperature for germination is 18-21°C. Maize grows in a temperature range from 14-40°C. The optimum temperature range for growth is 18-32°C. Rainfall should be 500-1200mm in a growing cycle to become an optimum water supply. No excessive relative humidity (RH) is favorable. Maize grows on many forms of soils. Well drained, well aerated, deep loam and silt loam soils with adequate organic matter are most suitable for cropping.

2.6.2. Requirements of mungbean (Phaseolus vulgaris)

Mungbean is not grown in the lowland humid tropics. The optimum temperature ranges from 15-20°C. Soil temperature for germination should be higher than 15°C. Mungbeans are sensitive to frost and to temperatures higher than 30°C. The total precipitation should be 400-500mm per growing cycle. Dry weather is required at harvest. Excessive rain causes flower drop and diseases. Medium to high RH is required, especially at flowering. The optimum texture is loam to clay loam. The crop is sensitive to water logging, so the soils should be well drained.

2.6.3. Requirements of rice (Oryza sativa)

Rice is generally considered as a tropical crop and is the most productive cereal growing in Asia on land from below the sea level to 2700m elevation. The average temperature for rice cultivation has to exceed 20°C and the minimum temperature has to exceed 10°C for 4-6 months. The optimum temperature for rice growth is 30-32°C. Rice needs generous rainfall or irrigation. In tropical countries the crops receive high rainfall (1000-1400mm). High relative humidity favors crop growth through the vegetative stage but also favors diseases. Low RH causes shrunken grains. Light is not a limiting factor to growth in the early stages but becomes progressively more critical with the age of the plant. Throughout the growing period the sum of hours of sun is approximately 1200 hours. The intensity of sunshine should be higher in the later stages of the growth. The requirements of the slope and landform for the cultivation depend on the type of rice culture.
3. MATERIALS AND METHODS

3.1. Study area

The study was carried out in Long Khanh village, Cai Lay district, Tien Giang province, and belongs to the Mekong Delta, Vietnam (Figure 3.1, Figure 3.2).

Figure 3.1: Map of the Mekong Delta Vietnam, with the study location.
Chapter 3: Materials and methods

The study location is in the southern part of Cai Lay district and belongs to the major region of alluvial soils in the Mekong Delta. The total annual precipitation is between 1,200 mm and 1,500 mm and the total annual evaporation between 1,200 and 1,400 mm. The temperatures are stable throughout the year and vary from 25 to 28°C average. Average radiation is 162Kcal/cm²/year and there are about 2,709 hours of sunshine/year. Most of these climatic factors are favorable for agriculture and crop growth (Tran Ba, 2004).

The area is supplied by fresh water through a network of canals and the flooding period is at the end of September. Flooding depth of this region ranges from 20-50 cm (Tran Ba, 2004).

Figure 3.3 shows the monthly average rainfall and temperature of the study location (station My Tho, Tien Giang) at latitude 10°22'51'' N and longitude 106°07'03'' E, with an elevation of 2m.
Chapter 3: Materials and methods

The climate has optimal conditions for rice cultivation, especially during the wet season (June till November, crop 1 and 3 in section 4.4.2.). The temperatures are always between 20 and 35°C, what is a preferable temperature range for rice, maize and mungbean growth. Mungbeans need only 400-500 mm precipitation per growing cycle (crop 2 in section 4.4.2.) and are normally cultivated from March till June. Maize needs more precipitation and the best growing season would be from June till September (crop 3 in section 4.4.2.). If maize is cultivated in another period, additional irrigation is necessary.

All the soil samples were taken in the beginning of July, after harvest of the upland crops. In this period of the year it is rainy season and conditions of the water content of the soil varies from field capacity to saturation.

3.2. Experimental design
The experiment-fields with different land use and land management practices were arranged in a randomized complete block design with four replications. Each plot has an area of exact 42 m². The six different treatments were:

- Rice-rice-rice
- Rice-rice-rice+10 tons organic manure/crop season
- Rice-maize-rice
- Rice-maize (+10 tons organic manure)-rice
- Rice-mungbean-rice
- Rice-mungbean-maize
Chapter 3: Materials and methods

For upland crops, beds of a height of 20 cm above the field surface were prepared, with the use of the soil next to the beds. This provided rotation of soil between the Ap and AB-horizon. Before sowing of rice crops, the soil was aligned and tilled.

The soil at the experimental field has been classified as Gleyic Fluvisols (Soil Science Department, Can Tho University, 2005; Soil Survey Staff, 1998) based on USDA/Soil Taxonomy Classification system (1996). All master soil horizons have been described using the Guidelines of FAO/UNESCO (1990) and thus considering following morphological characteristics: soil matrix color (field conditions), soil matrix color (wet and dry conditions), soil texture, development of soil mottling patterns and their characteristics, soil structure, soil consistency, soil ripening, bio-pore system, concretions and abundance and distribution of the roots.

The top soil showed an accumulation of brown alluvial material, mixed with common brown fresh roots. Soil was ripe and nearly ripe down to the depth of 130 cm. From the depth of 130 cm, the texture was sandy loam. The profile descriptions were performed by Tran Ba Linh in 2003 and are described in Appendix A.1. The 20-30 cm depth was the AB-horizon (20/25-45/55 cm) for the rice monoculture treatments. In the treatments with upland crops this layer was mixed with the Ap-horizon (0-20/25 cm) because beds were used. The beds were dug from the AB-horizon, which provided a good soil mixing and decreased the possibility on a compacted layer.

Table 3.1 gives the chemical properties of the organic manure used in treatment R-R-R+OM and R-M-R+OM. The composition might influence the chemical soil characteristics.

<table>
<thead>
<tr>
<th>C (%)</th>
<th>pH</th>
<th>EC (µS/cm)</th>
<th>N_{total} (%)</th>
<th>C/N</th>
<th>P_{total} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.9</td>
<td>7.5</td>
<td>2,068</td>
<td>2.32</td>
<td>19.78</td>
<td>2.56</td>
</tr>
</tbody>
</table>

PH and EC of the organic manure were higher than pH and EC of the soil at the study location, which means that addition of organic manure could have an influence on these parameters. The high carbon content of the manure can also affect the SOC-content of the soil.

3.3. Field survey

Local farmers have been interviewed at the selected study site and from surrounding areas with alluvial soils as the major soil group. The purpose of this investigation was to collect information about former and present land use systems and land management practices. The interviews were taken from 109 farmers. These include four types of land use: 3 rice crops/year, 3 upland
crops/year, 1 rice and 2 upland crops/year, 2 rice and 1 upland crop/year. For the cultivation of 3 upland crops/year 19 farmers were interviewed and for the other types of land use, 30 farmers were interviewed.

In the interview sheets following information was collected:

- The history of people’s settlement and exploitation, and land use system development.
- Farming system analysis: cropping pattern and types of cultivation.
- Cultivation techniques and land management: soil preparation for cultivation (ploughing, digging, how deep, duration application, number of times per year), ways to level the soil surface, application of fertilizers (type, amount, number and methods of application), irrigation and drainage (ways, methods and water quality of the irrigated water), other soil preparations influencing the soil characteristics.
- Limiting factors of plant yield and soil productivity (according to local farmers and others concerned).
- Rice yield and total cost of cultivation to calculate economic efficiency of the different land management practices.

3.4. Soil analysis

3.4.1. Field measurements
Soil strength (i.e. soil penetration resistance) has been measured with an electronic penetrometer (Eijkelkamp, Agrisearch Equipment, Giesbeek, The Netherlands), directly in the field to characterize soil strength resulting from the cohesive forces between soil particles and their frictional resistance. These measurements have been repeated four times, with three replicates per land use system or land management practice.

3.4.2. Soil sampling
Undisturbed soil samples were taken with rings of a volume of 98,125 cm³. Two rings per plot were used, with four replications at six different land uses and managements, at three depths (0-10 cm, 10-20 cm and 20-30 cm). These rings have been used to determine most of the physical parameters.

About three kg of disturbed soil was taken per replicate and per land use and management system at three depths (0-10 cm, 10-20 cm and 10-30 cm) for chemical and other physical analysis. Every sample was a randomized composition from ten locations within one plot. All the samples were air-dried in the storage room of the Department of Soil Science, College of Agriculture and Applied Biology, Can Tho University.
3.4.3. Chemical soil analysis
The chemical soil properties were analyzed on sieved (<1mm) disturbed soil samples.

For the determination of the pH in the soil, 10 g of soil was extracted by 50 ml of distilled water (1/5) and measured with a pH Meter (OKAION pH/mV/C0 meter, Eutech Instruments, Nijkerk, The Netherlands).

The Electric Conductivity of the soil (EC) was measured with an EC-meter (Schott Instruments D-55122, Mainz, Germany) on the extract of soil with water (1/5).

The Cation Exchange Capacity (CEC) was determined with the method of Gilman (1979). Barium (from BaCl$_2$) was used to remove the adsorbed cations, afterwards Barium was precipitated as BaSO$_4$, with MgSO$_4$. The amount of magnesium-ions was used to calculate the CEC. These values are expressed in cmol(+)/kg soil.

Soil Organic Carbon (SOC) was determined by the Walkley and Black method (1934). The organic carbon of the soil was oxidized by K$_2$Cr$_2$O$_7$. In the second step the excess of Cr$_2$O$_7^{2-}$ was titrated with FeSO$_4$. The efficiency of this method is 75%.

Labile C was calculated by the subtraction of hydrolysable carbon from SOC. The hydrolysable carbon was determined with the acid hydrolysis method.

Available nitrogen, i.e. the amount of organic nitrogen and the amount of ammonia in the soil, was extracted by KCl and was measured with a colorimeter (Shimadzu UV-1800): N-NH$_4^+$ at 640 nm and N-NO$_3^-$ at 543 nm.

Available Phosphor was determined with the Bray and Kurtz method (1945). This includes an extraction with NH$_4$F dissolved in distilled water (at pH 2.6) and a measurement with the colorimeter (Shimadzu UV-1800) to analyze for P.

For total acidity (cmol/kg), soil was extracted with KCl 1N and titrated by NaOH 0.01N.

3.4.4. Soil physical analysis

3.4.4.1. Soil Texture
First, the soil sample was air dried and sieved with a sieve of 2 mm. Then soil organic matter was destroyed by H$_2$O$_2$. The Robinson pipette method (Klute, 1986) was used to analyze the soil particle size distribution. Based upon Stokes Law the different particle sizes were minutely collected and measured at regular time intervals.
Chapter 3: Materials and methods

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 calculated and the texture triangle of USDA/Soil Taxonomy (Soil Survey Staff, 1998) was used to classify soil texture.

### 3.4.4.2. Soil Bulk Density, $\rho_b$

Dry bulk density ($\rho_b$) was calculated as dried soil weight (oven dried at 105°C) per bulk volume unit using the core method (Grossman and Reinsch, 2002). Undisturbed soil samples (volume of 98.125 cm³) were used.

### 3.4.4.3. Soil Particle Density, $\rho_p$

A pycnometer was used to determine the soil particle density, $\rho_p$. The soil fraction (< 2 mm) was oven-dried and a 50 ml pycnometric flask was used to analyze the soil particle density.

### 3.4.4.4. Soil Porosity

Porosity or Total Pore Volume Percentage was deduced and calculated from $\rho_b$ and $\rho_p$:

$$\Phi = \left(1 - \frac{\rho_b}{\rho_p}\right) \times 100$$

### 3.4.4.5. Volumetric Water Content, $\Theta$

The volumetric water content ($\Theta$) is the amount of water present in the soil sample. The initial weight of the undisturbed soil samples and the oven-dried weight were used to calculate the amount of water in the initial sample:

$$\Theta = \frac{V_{aq}}{V_i}$$

In which $\Theta$ is the volumetric water content (m³/m³), $V_{aq}$ is the water volume in the initial sample (m³) and $V_i$ is the initial soil bulk volume (m³).

### 3.4.4.6. Water Retention Curve

The water retention curve was experimentally established at seven matric potentials: -1 kPa, -30 kPa, -5 kPa, -10 kPa, -33 kPa, -100 kPa and -1500 kPa.

The sand-box apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) was used to determine matric potentials between -1 and -10 kPa, whereas pressure chambers (Soil moisture Equipment, Santa Barbara CA, USA) were used for matric potentials ranging from -33 to -1500 kPa, following the procedure described in Cornelis et al. (2005). Hydraulic equilibrium between the applied pressure and soil water content was reached after 7 days.
Chapter 3: Materials and methods

The van Genuchten equation (1980), an effective and commonly used parametric model for relating water content to matrix potential, was fitted to the measured water retention data:

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

in which \(\theta\) is the water content (m³/m³), \(h\) is the matrix potential (cm), \(\theta_r\) is the residual water content (m³/m³), \(\theta_s\) is the water content at saturation (m³/m³), \(\alpha\), \(n\), \(m\) are parameters directly dependent on the shape of the \(\theta(h)\) curve, \(m = 1 - 1/n\), and with \(\alpha\) in cm⁻¹.

3.4.4.7. Soil Macro-porosity and Matrix Porosity

Macro-porosity (MacPOR) and matrix porosity (MatPOR) parameters define the volume of soil macro-pores and matrix pores:

\[
\text{MacPOR} = \theta_s - \text{MatPOR} \\
\text{MatPOR} = \theta_m
\]

with:

\(\theta_m\) saturated volumetric water content of soil matrix, exclusive of macro-pores (m³/m³).

Matric potential values of -10, -5 and -1 kPa were used to determine \(\theta_m\), as suggested in Reynolds et al. (2007). These values correspond to pore diameters greater than 0.03, 0.06 and 0.3 mm, respectively.

3.4.4.8. Air Capacity

Soil air capacity (AC) is an indicator for the grade of aeration:

\[
\text{AC} = \theta_s - \theta_{fc}
\]

with:

\(\theta_s\) water content at saturation (m³/m³)
\(\theta_{fc}\) water content at field capacity (m³/m³)

A matric potential of -33 kPa was taken as field capacity (Romano and Santini, 2002).

3.4.4.9. Plant Available Water Capacity

The plant-available water capacity (PAWC) was used as an indicator for soil’s capacity to store and provide water to plant roots:

\[
\text{PAWC} = \theta_{fc} - \theta_{pwp}
\]
3.4.4.10. Relative Water Capacity

The relative water capacity (RWC) was used to express soil’s capacity to store water and air, relative to its total pore volume (i.e. the water content at saturation, $\theta_s$):

$$RWC = \frac{\theta_{fc}}{\theta_s} = \left[ 1 - \frac{\theta_{FC}}{\theta_s} \right]$$

3.4.4.11. Aggregate stability

The stability of the aggregates was measured on air dried soil samples using the dried and wet sieving method of De Leenheer and De Boodt (1959). Sieve fractions of 8.0-4.76 mm, 4.76-2.8 mm and 2.8-2.0 mm were collected. The difference in the weighted quantities of the aggregate sizes between dry and wet sieving is an index for aggregate instability:

$$IS = MWD_d - MWD_w$$

with:

$$MWD = \frac{\sum mi \cdot di}{\sum mi}$$

in which:

$IS$ Instability Index

$MWD$ Mean Weighted Diameter of the dry (d) and wet (w) aggregate fractions

$mi$ mass of the aggregate fraction i (g)

$di$ mean diameter of the aggregate fraction i (mm)

The stability index was expressed as:

$$SI = \frac{1}{IS}$$

and the Stability Quotient represents for structural stability:

$$SQ = SI \times (% \text{ aggregates } > 2 \text{ mm})$$

Additionally, aggregate stability was measured with the three methods of Le Bissonnais (1996): fast wetting, slow wetting and mechanical breakdown by shaking after pre-wetting.
Chapter 3: Materials and methods

3.4.4.12. Atterberg limits

Atterberg (1911) divided soils in consistency zones, depending on their water content. The most important limits are the plastic limit and the liquid limit and were tested in the laboratory, from which the plastic index was calculated.

The plastic limit (PL) is the water content of the soil when its behavior changes from brittle to plastic. The soil is at its plastic limit when a 3 mm diameter rod is beginning to crumble while rolling it, upon which its water content was determined gravimetrically at 105 °C (ASTM D 4138, 1989).

The liquid limit (LL) is the water content of the soil at which the soil changes from plastic to liquid behavior and was determined using a Casagrande device (ASTM D4318, 2003). A 12-mm deep groove was made through the soil which was brought in to the cup of the device and subsequently the cup was dropped from 12 mm. Water was added until it was sufficient to become between 30 and 40 drops to cause closure of the groove.

The plasticity index (PI, ASTM D 4138, 1989) is a measure of the plasticity of the soil. This index is the size of the range of water contents where the soil exhibits plastic properties and is calculated as the difference between LL and PL. Soils with a high plasticity index are clayey soils (>15), a lower PI tend to be soils with more silt (<10) and soils with PI=0 possesses no silt or clay.

3.4.4.13. S-index

The S-index of Dexter (2004a,b,c) represents the magnitude of the slope of the soil water retention curve at the inflection point. The curve has to be expressed as gravimetric water content, θg (in kg/kg) versus the natural logarithm of the matrix potential, ln(h) (cm, h > 0). Soil physical degradation is made visible with the S-index; e.g. when soil is compacted, the slope of the retention curve at the inflection point is reduced.

The S-index was evaluated using equation:

\[
S = n \ast (\theta_s - \theta_r) \ast \left(\frac{2n - 1}{n - 1}\right)^{\frac{1}{n-2}}
\]

where n, θs, θr are the Van Genuchten parameters. θr was set to 0 before the estimation of the other parameters, as suggested by Dexter (2004b).
3.5. Statistical analysis
Effects of land management strategies on physical and chemical properties were analyzed by the one way analysis of variance (ANOVA) for the randomized complete block design. When treatments main effects occurred, significant differences were determined using the Duncan’s multiple range test at 0.05% significance level. The standard deviation was also calculated and denoted by error bars on the graphs and bar charts to indicate the variability about the mean values. The analysis of variance, the differences between the means and the interaction between the means were tested using SPSS 17 (SPSS Inc.).
4. RESULTS AND DISCUSSION

4.1. Chemical soil properties

The soil at the study location had a pH between 5.15 and 5.70 and did not show any significant difference between the different horizons or treatments. For coarse-textured soils with low clay content a higher pH is important to increase the total number of charges on the colloids so that higher nutrient concentrations are retained in the soil (Arthur et al., 2011). Since the soil at the study location had a high clay content, this quite low pH has no specific constraints for crop growth.

Table 4.1 and Table 4.2 give the chemical properties for six different treatments at three depths.

Electric conductivity (EC; Table 4.1) was not significantly different between the treatments and the horizons (between 525.0 µS/cm and 738.8 µS/cm), with exception of R-Mb-M at horizon 10-20 cm where EC was significantly lower (404.0 µS/cm) than in all other treatments and horizons. At the other depths a lower EC is also visible for this treatments, though not significant. The salts could be washed out because of the better drainage due to the bed-formation for the two upland crop cultivations, which lowers the EC. As a general guideline, an EC level between 200-1200 µS/cm is a good range for growing crops. Lower than 200 µS/cm would indicate low nutrient levels and low microbial activity. EC higher than the optimum range would mean too high salt concentrations, because of overuse of high salt fertilizer or due to lack of drainage (Agriculture Solutions, 2011).

The soil organic carbon content (SOC; Table 4.1) significantly declined with the depth in all the treatments. The rotations with added organic manure per crop season did not show significant difference with the same rotation without the added organic manure. The organic manure has only been applied for four years and this might be the reason that there was no build up in SOC-content. However, Dalal and Chan (2001) stated that added organic manure directly influences the crop productivity. The SOC-content in R-R-R at the top horizon was significantly higher than at the top horizon of R-M-R, R-M-R+OM and R-Mb-R. This can be explained by the lower oxygen concentration (caused by the higher water level) in rice fields, which slows down the mineralization rate. R-Mb-M had significantly lower SOC than all other treatments. Upland crops bring no organic carbon in the soil, while after harvesting of rice the organic residues stay in the soil. This makes that the R-Mb-M rotation (2 upland crops) had a lower SOC-content than the rotations with more rice cropping. At a depth of 10-20 and 20-30 cm, R-M-R(+OM) had a
significantly higher SOC-content than R-R-R(+OM). This can be explained by the higher soil mixing rate in rotations with upland crops in comparison with rice monoculture. In the research from Arthur et al. (2011) the SOC-values are between 1.5% and 2% for sandy soils, which is slightly lower than in this study on clayey soils. For the clayey Vertisols in Tasmania (Cotching et al., 2001) the OC-content is higher (2.5%-8%) and the values of our study are in the lower part of this range. There exists a positive correlation between OC and clay-content. The soil is in Tasmania have a slightly lower clay-content, so it can be determined that the OC-values are quite low for our study.

Table 4.1: Chemical properties for six different treatments, at three different depths: EC, CEC, SOC, labile C.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Horizon (cm)</th>
<th>EC (µS/cm)</th>
<th>CEC (cmol/kg)</th>
<th>SOC (%)</th>
<th>C labile (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-R-R</td>
<td>0-10</td>
<td>661.6(81.28)</td>
<td>21.21(0.44)</td>
<td>3.17(0.14)</td>
<td>0.150(0.04)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>623.9(47.93)</td>
<td>21.76(0.81)</td>
<td>1.57(0.21)</td>
<td>0.067(0.03)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>625.0(60.93)</td>
<td>24.02(1.73)</td>
<td>1.03(0.11)</td>
<td>0.042(0.02)</td>
</tr>
<tr>
<td>R-R-R+OM</td>
<td>0-10</td>
<td>684.4(120.97)</td>
<td>23.36(0.92)</td>
<td>3.20(0.22)</td>
<td>0.374(0.06)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>601.0(61.14)</td>
<td>23.71(1.67)</td>
<td>1.56(0.16)</td>
<td>0.092(0.03)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>650.0(93.34)</td>
<td>23.96(0.60)</td>
<td>1.15(0.16)</td>
<td>0.067(0.03)</td>
</tr>
<tr>
<td>R-M-R</td>
<td>0-10</td>
<td>671.0(140.55)</td>
<td>22.90(1.12)</td>
<td>2.77(0.19)</td>
<td>0.449(0.11)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>626.0(49.48)</td>
<td>23.21(1.03)</td>
<td>2.86(0.19)</td>
<td>0.333(0.10)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>711.9(137.13)</td>
<td>22.19(1.19)</td>
<td>2.35(0.28)</td>
<td>0.167(0.05)</td>
</tr>
<tr>
<td>R-M-R+OM</td>
<td>0-10</td>
<td>680.1(114.00)</td>
<td>22.79(1.39)</td>
<td>2.82(0.12)</td>
<td>0.449(0.10)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>629.6(60.74)</td>
<td>22.03(0.42)</td>
<td>2.87(0.12)</td>
<td>0.324(0.07)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>607.8(96.56)</td>
<td>22.49(0.83)</td>
<td>2.38(0.20)</td>
<td>0.208(0.03)</td>
</tr>
<tr>
<td>R-Mb-R</td>
<td>0-10</td>
<td>738.8(54.46)</td>
<td>23.40(1.74)</td>
<td>2.74(0.16)</td>
<td>0.358(0.06)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>614.8(8.89)</td>
<td>23.84(1.38)</td>
<td>2.86(0.40)</td>
<td>0.241(0.08)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>699.4(172.29)</td>
<td>22.40(0.93)</td>
<td>2.02(0.11)</td>
<td>0.142(0.06)</td>
</tr>
<tr>
<td>R-Mb-M</td>
<td>0-10</td>
<td>585.4(73.83)</td>
<td>24.48(1.07)</td>
<td>2.11(0.11)</td>
<td>0.316(0.04)</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>404.0(58.31)</td>
<td>23.54(1.55)</td>
<td>2.22(0.10)</td>
<td>0.183(0.08)</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>525.0(85.39)</td>
<td>24.50(0.79)</td>
<td>1.81(0.17)</td>
<td>0.141(0.05)</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; EC, electrical conductivity; CEC, cation exchange capacity; OM, organic matter content; C labile, labile carbon content. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; a, b, c, d are the significant differences between the rotations; x, y, z are the significant differences between the horizons. Numbers between brackets represent the standard deviations.
Chapter 4: Results and discussion

The R-R-R treatment showed a significant lower cation exchange capacity (CEC; Table 4.1) than R-R-R+OM, R-Mb-R and R-Mb-M in the upper horizon (13-9% lower). At depth 10-20 cm this significant difference was still visible between R-R-R and R-Mb-R (decrease of 9%). For all the treatments the CEC was medium to high (between 21.0 and 24.5 cmol/kg; Brady and Weil, 2002) because the soil has a high clay content.

The CEC was significantly higher (12%) for depth 20-30 cm in comparison with the upper depths, in the rice monoculture treatment. This observation is in contrast with the expected result that SOC makes a contribution to CEC what has been encountered by Dalal and Chan (2001) and Cotching et al. (2002). The contradictory result might be due to the contribution of the higher clay-content (Table 4.3) in horizon 20-30 cm. The clay content in rice monoculture treatment is higher at a higher depth because no mixing occurs between the different rice cultivations and clay sinks down in the soil because of its small particle diameter. The fact that no significant difference in CEC was observed for R-R-R+OM can be explained by the high CEC of the SOC in the upper horizons and the high clay content that contribute to a higher CEC in the lowest horizon. All the other treatments showed no significant difference between the horizons.

Labile C turns over more rapidly and is a better indicator for soil quality than SOC (Hoyle, 2006). In all the treatments labile C, as SOC, was significantly decreasing with depth. Between the treatments at a depth of 0-10 cm, labile C was significantly higher for R-M-R(+OM) than for R-Mb-M. Remarkable is that all the treatments had a significantly higher labile C than R-R-R at depth 0-10 cm. At depth 10-20 cm and 20-30 cm, labile C was significantly lower for R-R-R(+OM) than for all the other treatments. This means that even though SOC was higher in R-R-R (+OM) than R-M-R(+OM) and R-Mb-R, and that SOC in R-Mb-R was higher than R-Mb-M, R-M-R(+OM) has a greater potential for nutrient turnover because of its higher labile C-content, followed by R-Mb-R and R-R-R+OM, R-Mb-M, R-R-R, respectively. Similarly, Kanema (2009) found highest labile C for maize, followed by other upland crops and a high decline in rice monoculture. High labile C influences the mass and the activity of micro-organisms, that have the capacity to release available N (Stine and Weil, 2002). This makes that similar trends are visible in the N\textsubscript{cv} data (Table 4.2).

Total acidity (TA; Table 4.2) was not significantly lower for the treatments with added organic manure. This is likely due to the high standard deviations, because the mean of the total acidity for R-R-R and R-M-R was 50% and 21% higher than for R-R-R+OM and R-M-R+OM, respectively. The added organic manure decreased the acidity because of its higher pH (Table 3.1). The total acidity of R-Mb-M was significantly lower than all other treatments at the upper horizon. During
the rice cropping, organic matter will be submerged in water and its decay produces H$_2$S, which increases the total acidity. This explains the lower TA in the rotation with two upland crops.

Table 4.2: Chemical properties for six different treatments, at three different depths: TA, N$_{av}$, P$_{av}$.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Horizon (cm)</th>
<th>TA (cmol/kg)</th>
<th>N$_{av}$ (mg/kg)</th>
<th>P$_{av}$ (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-R-R</td>
<td>0-10</td>
<td>0.421(0.305)$^a$</td>
<td>101.1(17.31)$^b$</td>
<td>82.0(15.22)$^b$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.418(0.323)$^a$</td>
<td>55.0(28.13)$^b$</td>
<td>26.8(9.35)$^d$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.227(0.390)</td>
<td>24.6(10.63)$^c$</td>
<td>8.9(1.82)$^d$</td>
</tr>
<tr>
<td>R-R-R+OM</td>
<td>0-10</td>
<td>0.212(0.173)$^{abc}$</td>
<td>143.0(41.16)$^b$</td>
<td>123.5(25.20)$^c$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.211(0.224)$^{ab}$</td>
<td>49.1(24.70)$^b$</td>
<td>22.2(7.06)$^d$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.117(0.148)</td>
<td>19.0(10.63)$^c$</td>
<td>10.2(2.71)$^d$</td>
</tr>
<tr>
<td>R-M</td>
<td>0-10</td>
<td>0.371(0.099)$^{abc}$</td>
<td>239.9(63.87)$^a$</td>
<td>67.3(8.66)$^b$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.185(0.102)$^{ab}$</td>
<td>162.2(60.22)$^a$</td>
<td>62.9(7.58)$^b$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.401(0.061)</td>
<td>121.0(27.55)$^a$</td>
<td>48.2(4.40)$^a$</td>
</tr>
<tr>
<td>R-M-R+OM</td>
<td>0-10</td>
<td>0.292(0.174)$^{abc}$</td>
<td>257.3(75.87)$^a$</td>
<td>68.9(1.15)$^b$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.196(0.083)$^{ab}$</td>
<td>152.8(39.54)$^a$</td>
<td>64.2(10.31)$^b$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.277(0.061)</td>
<td>109.3(39.32)$^a$</td>
<td>52.4(3.09)$^a$</td>
</tr>
<tr>
<td>R-Mb-R</td>
<td>0-10</td>
<td>0.133(0.080)$^{abc}$</td>
<td>159.1(28.86)$^b$</td>
<td>55.8(11.84)$^d$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.063(0.031)$^{ab}$</td>
<td>151.2(45.85)$^b$</td>
<td>51.4(8.69)$^b$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.230(0.139)</td>
<td>63.8(14.08)$^b$</td>
<td>39.3(1.26)$^b$</td>
</tr>
<tr>
<td>R-Mb-M</td>
<td>0-10</td>
<td>0.033(0.029)$^{c}$</td>
<td>110.8(24.24)$^b$</td>
<td>41.5(7.82)$^d$</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.062(0.060)$^{b}$</td>
<td>77.2(15.89)$^b$</td>
<td>39.4(2.55)$^c$</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.176(0.109)</td>
<td>58.2(16.82)$^b$</td>
<td>32.8(5.24)$^e$</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; TA, total acidity; Nav, available nitrogen; Pav, available phosphor. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; a, b, c, d are the significant differences between the rotations; x, y, z are the significant differences between the horizons. Numbers between brackets represent the standard deviations.

Available nitrogen (N$_{av}$; Table 4.2) decreased significantly with the depth, in all treatments (47-86%). For the upper horizon, N$_{av}$ was significantly higher for R-M-R(+OM) (61 to 34% higher) in comparison with all other treatments. At depth 10-20 cm, the same observation is true for R-M-R(+OM) and R-Mb-R (49-69% higher N$_{av}$ than all other treatments). At depth 20-30 cm, the available nitrogen in R-M-R(+OM) was significantly higher (41-52% higher) than in R-Mb-R and R-Mb-M, and N$_{av}$ in R-Mb-R and R-Mb-M was significantly higher (58-70% higher) than in R-R-R(+OM). These differences in N$_{av}$ can be explained by the difference in labile C that influences the microbial activity. The low available nitrogen in rice monoculture is due to the high water table and similar results have been observed in a study of Olk et al. (1995).
Chapter 4: Results and discussion

For available phosphor ($P_{av}$; Table 4.2), a significant decrease of 89-92% was observed between the upper horizon and the 20-30 depth in $R-R-R(+OM)$. The same trend was visible in $R-M-R(+OM)$ and $R-Mb-R$, but with a decrease of 30-24%. $R-Mb-M$ showed no significant difference in $P_{av}$ between the depths. At the upper horizon, $R-R-R+OM$ recorded the significantly highest $P_{av}$ (34 to 66% higher), followed by $R-R-R$ (up to 33% higher), in comparison with the other treatments. For depth 10-20 and 20-30 cm, treatment $R-R-R(+OM)$ had significantly lower $P_{av}$ (up to 86%) than all other treatments, followed by $R-Mb-M$ which had a significantly lower $P_{av}$ than $R-M-R(+OM)$ and $R-Mb-R$ (up to 49% lower). At this depth $R-Mb-R$ was also significantly lower than $R-M-R(+OM)$ (to 39% lower). The high decrease of $P_{av}$ observed in $R-R-R(+OM)$ might be due to little mixing of the soil between the different cropping seasons. The higher level of $P_{av}$ in the upper horizon is due to the rice roots and straw that stay incorporated in the soil after harvesting. As they decay, they release nutrients, available for the next crops (Schueneman et al., 2008). Upland crops consume more nutrients and this explains the lower $P_{av}$ in a rotation with two upland crops ($R-Mb-M$).

4.2. Physical soil properties and characteristics

4.2.1. Soil texture
The soil textural class of the whole experimental area was clay, with a mean of 2.3% sand, 31.3% loam and 66.4% clay. Heavy clayey soil are fine-textured and have a different soil physical behavior than silt or sandy soils. Clay has typical higher organic matter content, lower hydraulic conductivity, higher porosity, lower bulk density and higher water holding capacity than sandy soils (Brady, 1998).

4.2.2. Bulk density, soil porosity, particle density and volumetric water content at saturation
Soil bulk density (Figure 4.1), soil porosity and particle density (Table 4.3) were used to estimate compaction and soil aeration.

Density of the volume of the dry soil as it naturally exists, or bulk density, includes air space and organic carbon but not soil moisture. This value is dependent on soil texture, SOC-content, root penetration and soil structure. For fine-textured soils, the optimal bulk density for crop production ranges from 0.9 to 1.2 Mg/m³ (Reynolds et al., 2007).
Chapter 4: Results and discussion

Figure 4.1: Bulk density for six different treatments, at three depths. R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; a, b, c are the significant differences between the rotations; the significant differences between the horizons are not included in the figure. Error bars represent the standard deviations.

Soil bulk density was significantly lower (19% decrease) for the upper horizon in the R-R-R(+)OM rotation in comparison with the 10-30 cm depths. Compaction at 20-30 cm (for R-R-R and R-R-R+OM $\rho_b$ is 1.30 Mg/m$^3$ and 1.32 Mg/m$^3$, respectively) can impose mechanical root penetration in the soil and rice plants fall down during growth. This makes harvest difficult. Rotations with upland crops provides a higher rate of soil mixing and thus bulk density was similar at different depths and significantly lower than in rice monoculture at a depth of 10-30 cm. The R-Mb-M treatment had a slightly higher bulk density (5% increase) than the other rotations with upland crops. In this rotation with two upland crops, the upland crops do not add OC to the soil so that less SOC was contributed to the soil, what might increase bulk density. The correlation between bulk density and organic carbon was high (r=0.85) for this study location. Similar differences due to differences in SOC have been observed in the study of Reynolds et al. (2007). Cotching et al. (2002) also perceived a negative correlation between organic carbon and bulk density.

Particle density of a soil is the average density of the individual soil grains. This parameter depends on the accumulative density of the individual inorganic constituents of the soil and OC-content tends to lower the overall particle density.
Chapter 4: Results and discussion

Table 4.3: Particle density, total porosity and clay content for the six different treatments, at three different depths.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>( \rho_p ) (Mg/m³)</th>
<th>( \Phi ) (%)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R-R-R</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.393(0.03) ( ^b ) ( ^y )</td>
<td>62.09(1.41) ( ^z )</td>
<td>65.30(1.21) ( ^b )</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.474(0.04) ( ^z )</td>
<td>54.24(2.02) ( ^c ) ( ^y )</td>
<td>67.94(1.86) ( ^b )</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.528(0.02) ( ^z ) ( ^x )</td>
<td>47.67(2.10) ( ^z ) ( ^c )</td>
<td>69.77(2.14) ( ^b )</td>
</tr>
<tr>
<td><strong>R-R-R+OM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.385(0.01) ( ^b ) ( ^x )</td>
<td>62.13(1.28) ( ^z ) ( ^x )</td>
<td>66.40(1.80) ( ^b )</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.477(0.01) ( ^y )</td>
<td>54.89(1.07) ( ^c ) ( ^y )</td>
<td>69.01(1.48) ( ^b )</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.513(0.01) ( ^ab ) ( ^z ) ( ^x )</td>
<td>48.17(2.35) ( ^c ) ( ^x )</td>
<td>70.16(1.80) ( ^b )</td>
</tr>
<tr>
<td><strong>R-M-R</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.450(0.03) ( ^a )</td>
<td>60.74(2.17) ( ^a ) ( ^z )</td>
<td>65.09(1.03)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.477(0.01) ( ^c )</td>
<td>62.08(2.28) ( ^a ) ( ^z )</td>
<td>64.56(1.66)</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.486(0.05) ( ^abc ) ( ^c ) ( ^z ) ( ^x )</td>
<td>61.40(2.77) ( ^a ) ( ^z ) ( ^c )</td>
<td>66.08(1.58)</td>
</tr>
<tr>
<td><strong>R-M-R+OM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.461(0.04) ( ^a )</td>
<td>61.29(1.90) ( ^a ) ( ^z )</td>
<td>65.59(1.51)</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.469(0.02) ( ^c )</td>
<td>63.93(2.19) ( ^a ) ( ^z )</td>
<td>63.55(2.98)</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.492(0.03) ( ^abc ) ( ^c ) ( ^z ) ( ^x )</td>
<td>62.55(1.41) ( ^a ) ( ^z ) ( ^c )</td>
<td>66.49(0.84)</td>
</tr>
<tr>
<td><strong>R-Mb-R</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.461(0.05) ( ^a )</td>
<td>61.26(2.63) ( ^a ) ( ^z )</td>
<td>64.01(2.72) ( ^b )</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.475(0.05) ( ^c )</td>
<td>62.86(1.54) ( ^a ) ( ^z )</td>
<td>66.65(1.67) ( ^b )</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.465(0.04) ( ^bc ) ( ^c ) ( ^z ) ( ^x )</td>
<td>59.77(1.54) ( ^c ) ( ^c ) ( ^z ) ( ^x )</td>
<td>68.38(2.15) ( ^b )</td>
</tr>
<tr>
<td><strong>R-Mb-M</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-10 cm</td>
<td>2.469(0.04) ( ^a )</td>
<td>59.05(1.55) ( ^a ) ( ^z )</td>
<td>64.66(1.12) ( ^b )</td>
</tr>
<tr>
<td>10-20 cm</td>
<td>2.463(0.06) ( ^c )</td>
<td>59.32(1.46) ( ^b ) ( ^x )</td>
<td>66.02(0.64) ( ^b )</td>
</tr>
<tr>
<td>20-30 cm</td>
<td>2.450(0.02) ( ^c ) ( ^c ) ( ^z ) ( ^x )</td>
<td>58.01(0.33) ( ^b ) ( ^c ) ( ^z ) ( ^x )</td>
<td>65.96(0.44) ( ^b )</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M+R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; \( \rho_p \), bulk density; \( \rho_p \), particle density; \( \Phi \), total porosity; Clay (%), clay content. Different letters in each column mean statistically significant differences at \( P \leq 0.05 \) using DMRT; \( a, b, c \) are the significant differences between the rotations; \( x, y, z \) are the significant differences between the horizons. Numbers between brackets represent the standard deviations.

The top horizon of the rice monoculture treatments R-R-R and R-R-R+OM had a significantly lower (2.39 Mg/m³ to 2.46 Mg/m³, i.e. 3% lower) particle density than the top horizons of the rotations with upland crops. In the upland crop rotations there was no significant difference between the horizons, and the rice monoculture treatment manifested a significant difference between the top and the underlying horizons. The high difference in OC-content between the horizons in R-R-R(+)OM (Table 4.1) might be the reason.

The soil porosity corresponds to the volume not occupied by organic or mineral solids. It is calculated from bulk and particle density and is, theoretically, equal to the volume percent of water at saturation. Ideal soils have a soil porosity of about 50 percent, with around 25 percent stored water (Brady, 1998). The significant differences between the horizons in R-R-R(+)OM are a direct result of the difference in bulk and particle density. At a depth of 10-30 cm the porosity
of R-Mb-M was significantly lower than R-M-R(+OM). The porosity in treatments R-R-R and R-R-R+OM was significantly lower than for all other treatments, at depth 10-30 cm, due to compaction. This follows the trend of the bulk density. The results of total porosity are similar to the ones in the research on clayey Vertisols in Tasmania of Cotching et al. (2002).

4.2.3. Matrix and Macro-porosity

Matrix pores are textural pores and are generally small in size. Textural porosity is defined by primary particles that form aggregates. Non-matrix pores or macro-pores origin from roots, animals and action of compressed air, and are not affected by soil texture. The volume of matrix pores is subject to soil wetness and the volume of macro-pores is not (Lal and Shukla, 2004).

No available minimum or optimum values for MatPOR have been defined in literature (Reynolds et al., 2007), which makes it difficult to draw final conclusions.

Matrix porosity (Figure 4.2) showed similar results when different matric potentials were used to define macro-pores (-1 kPa, -6 kPa, -10 kPa, corresponding to pores greater than 300 µm, 50 µm and 30 µm, respectively). R-Mb-M showed highest MatPOR for the upper horizon. This might be due to the higher mixing of the soil, which breaks down aggregates and thus stimulates matrix porosity. At depth 10-20 cm, MatPOR was significantly higher for R-R-R(+OM) and R-Mb-M than for R-M-R(+OM) and R-Mb-R. That rice cropping breaks down aggregates because of higher bulk density and the tillage before every cultivation of rice, which implies destruction of macro-pores, could explain the higher MatPOR at higher depths, as suggested by Reynolds et al. (2007).
Figure 4.2: Influence of six different crop rotations at three depths on soil matrix porosity. R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; MatPOR_{10,5,1}, soil matrix porosity corresponding to the percentage of pores, which retain water at matric potentials of -10 kPa (a), -5 kPa (b) and -1 kPa (c), respectively. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; a, b, c are the significant differences between the rotations; the significant differences between the horizons has not been shown. Error bars represent the standard deviations.
Formation and stabilization of macro-pores (Table 4.4) is strongly influenced by organic carbon-content and clay minerals, and thus by land use and soil management (Lal and Shukla, 2004). Minimum or optimum values for MacPOR have not yet been determined, but for the upper depth of fine textured soils MacPOR > 0.05-0.10 m³/m³ is defined as “undegraded” and MacPOR < 0.04 m³/m³ is “degraded” because of compaction or consolidation (Reynolds et al., 2007).

MacPOR showed significant differences between the depths at treatment R-M-R+OM. This significant decrease at depth 20-30 cm can be explained by the addition of organic manure at the top layer. The results of MacPOR for the different treatments showed the same trends of significant differences between the different suctions (-10 kPa, -5 kPa and -1 kPa).

The MacPOR-values of R-R-R and R-R-R+OM are lower than 0.05 m³/m³ at the three different matric potentials, thus the soil can be considered as degraded (except for MacPOR1,5 in R-R-R, at depth 20-30 cm). At matric potential of -5 and -1 kPa, the MacPOR for R-Mb-M showed values <0.05 m³/m³. The low MacPOR for R-R-R(+OM) can be explained by the higher tillage frequency and the unfavorable conditions of the compacted soil. For R-Mb-M the degradation might be due to the low OC-input and the high use of minerals by upland crops. R-M-R+OM showed the highest value for MacPOR10,5,1 (0.073, 0.063 and 0.059 m³/m³; respectively), which might be due to the positive influence of the alternation between dry and wet conditions. Similar to the findings in this study, Arthur et al. (2011) found that organic manure changes the distribution of pores to higher macro-porosity.

At depth 20-30 cm, the treatments had no significant different MacPOR. This might mean that at this depth the treatments had no influence on the macro-porosity, since clay-content (Table 4.3) was similar and labile C (Table 4.1) showed no great differences at this depth.
### Table 4.4: Influence of six different crop rotations at three depths on soil macro-porosity

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Horizon (cm)</th>
<th>MacPOR(_{10}) (m(^3)/m(^3))</th>
<th>MacPOR(_{5}) (m(^3)/m(^3))</th>
<th>MacPOR(_{1}) (m(^3)/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-R-R</td>
<td>0-10</td>
<td>0.048(0.001)(^{bc})</td>
<td>0.040(0.01)(^{bc})</td>
<td>0.036(0.01)(^{bc})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.059(0.01)(^{ab})</td>
<td>0.031(0.01)(^{ab})</td>
<td>0.026(0.01)(^{ab})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.065(0.03)</td>
<td>0.052(0.02)</td>
<td>0.038(0.01)</td>
</tr>
<tr>
<td>R-R-R+OM</td>
<td>0-10</td>
<td>0.040(0.01)(^{c})</td>
<td>0.030(0.001)(^{c})</td>
<td>0.022(0.001)(^{c})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.033(0.01)(^{b})</td>
<td>0.027(0.01)(^{b})</td>
<td>0.024(0.01)(^{b})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.049(0.02)</td>
<td>0.042(0.02)</td>
<td>0.037(0.02)</td>
</tr>
<tr>
<td>R-M-R</td>
<td>0-10</td>
<td>0.061(0.02)(^{a})</td>
<td>0.059(0.02)(^{a})</td>
<td>0.055(0.02)(^{a})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.056(0.01)(^{yz})</td>
<td>0.049(0.01)(^{yz})</td>
<td>0.043(0.01)(^{yz})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.053(0.02)</td>
<td>0.045(0.02)</td>
<td>0.038(0.02)</td>
</tr>
<tr>
<td>R-M-R+OM</td>
<td>0-10</td>
<td>0.073(0.02)(^{yz})</td>
<td>0.059(0.02)(^{yz})</td>
<td>0.059(0.02)(^{yz})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.056(0.01)(^{yz})</td>
<td>0.049(0.01)(^{yz})</td>
<td>0.043(0.01)(^{yz})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.044(0.02)(^{y})</td>
<td>0.035(0.01)(^{y})</td>
<td>0.028(0.01)(^{y})</td>
</tr>
<tr>
<td>R-Mb-R</td>
<td>0-10</td>
<td>0.061(0.01)(^{xyz})</td>
<td>0.053(0.01)(^{xyz})</td>
<td>0.047(0.01)(^{xyz})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.049(0.03)(^{xyz})</td>
<td>0.045(0.02)(^{xyz})</td>
<td>0.043(0.02)(^{xyz})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.039(0.01)(^{y})</td>
<td>0.029(0.01)(^{y})</td>
<td>0.022(0.01)(^{y})</td>
</tr>
<tr>
<td>R-Mb-M</td>
<td>0-10</td>
<td>0.053(0.01)(^{bc})</td>
<td>0.042(0.01)(^{bc})</td>
<td>0.035(0.01)(^{bc})</td>
</tr>
<tr>
<td></td>
<td>10-20</td>
<td>0.044(0.01)(^{ab})</td>
<td>0.032(0.01)(^{ab})</td>
<td>0.023(0.02)(^{b})</td>
</tr>
<tr>
<td></td>
<td>20-30</td>
<td>0.038(0.01)</td>
<td>0.028(0.01)</td>
<td>0.020(0.01)</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; MacPOR\(_{10}\), MacPOR\(_{5}\), MacPOR\(_{1}\) soil macro-porosity corresponding to the percentage of pores, which are drained at matric potential of -10, -5 and -1 kPa, respectively. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; \(^{a},^{b},^{c}\) are the significant differences between the rotations; \(^{x},^{y},^{z}\) are the significant differences between the horizons. Numbers between brackets represent the standard deviations.

#### 4.2.4. Atterberg limits

The plastic limit is the water content of the soil when it changes from brittle to plastic behavior and the liquid limit is the water content at the boundary where the mixture of soil and water flows as a liquid or behaves plastic (Brady, 1998). The plastic limit shows how the soil reacts in its shear strength when the water content increases.
Chapter 4: Results and discussion

Figure 4.3: Influence of six different crop rotations, at three depths on the plastic limit, the liquid limit and the plasticity index. R-R, rice-rice-rice rotation; R-R+OM, rice-rice-rice rotation +10 tons organic manure/crop season; R-M, rice-maize rotation; R-M+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; PL, plastic limit is the difference between the height of PI and LL; LL, liquid limit; PI, plasticity index (lower bar). Bars with the grey basis represent depth 0-10 cm, with white basis represent depth 10-20 cm and with black basis represent depth 20-30 cm. Different letters in each column mean statistically significant differences at $P \leq 0.05$ using DMRT; a, b, c, d are the significant differences for PL between the rotations; significant differences between the horizons are not shown in the figure. The error bars represent the standard deviations.

The plastic limit (PL, grey bars in Figure 4.3) decreased significantly with depth for R-R-R(+OM) and R-M-R. This might be due to the significant higher SOC-content in the upper layer. Malkawi et al. (1999) suggested that PL increases because the water adsorptive capacity increases, induced by the organic carbon. However, high OC-content also tends to decrease the water adsorptive capacity, due to the decreased total surface area, caused by aggregation with organic carbon. Since soil mostly has a smaller water adsorptive capacity compared to organic carbon, PL increases with higher OC (Malkawi et al., 1999). This also explains the significant higher PL for R-R-R(+OM) and R-M-R+OM compared to R-Mb-M, at the upper horizon and the significant lower PL for R-R-R(+OM) than all the other treatments at depths 10-30 cm. In Cotching et al. (2002) cropped paddocks had a significant lower PL than long term pasture treatments, because of lower organic carbon contents. Similar results have also been found in Cotching et al. (2001) for clayey Vertisols, with a high correlation between OC and PL ($r=0.95$). In our study, correlation between PL and OM was also high with $r=0.80$ (Figure 4.4).
Chapter 4: Results and discussion

4.2.5. Soil strength

Soil strength is the resistance capacity of the soil matrix against external applied pressure forces and is an important characteristic in agricultural soils, e.g. performance of implemented crops, root growth and least-limiting water range (Vanags et al., 2006). Soil strength also gives a measure for susceptibility of the soil to compaction. The results of the soil strength are presented in Figure 4.5.

![Graph showing the correlation between plastic limit (PL) and organic carbon (SOC). The equation of the line is y = 3.9503x + 19.906 with R² = 0.7975.]

Figure 4.4: correlation between plastic limit and organic carbon.

The liquid limit and the plasticity index showed no significant difference between the treatments and the horizons. PI was between 29% and 34% for all the treatments, which indicates that the soils had a high plasticity because of the high clay content.
Figure 4.5: Soil strength averaged for four replicates in rice-rice-rice (R-R-R) rotation, rice-rice-rice rotation+10 tons organic manure/crop season (R-R-R+OM), rice-maize-rice rotation (R-M-R), rice-maize (+10 tons organic manure)-rice (R-M-R+OM), rice-mungbean-rice rotation (R-Mb-R), rice-mungbean-maize rotation (R-Mb-M). Bars represent standard errors for each land use system.

The largest differences in soil strength have been observed at depth 20-50 cm. At these depths, measured soil strength increased strongly for R-R-R, followed by R-R-R+OM. The difference in soil strength between the other treatments was not significant. These findings are supported by the observed bulk density and total porosity, because of the compacted soil. The increase in soil strength declined under a depth of 35 cm, below the compacted layer. Similar results have been found in a study of Levi et al. (2010), in which the conventional row cropping had a much higher increase in soil strength (at depth 10-20 cm) in comparison with longleaf pine forest. In Levi’s study the increase in soil strength also declined under a depth of 30 cm, for both treatments. Cotching et al. (2002) found the penetration resistance to be significantly higher at depth 20-40 cm, for cropping with rigorous tillage compared to shallow tillage and long term pasture.

The soil strength values were very high. These high values might be partially due to the low moisture contents at higher depths (> 30 cm) during field measurements (average between 0.47 m$^3$ m$^{-3}$ and 0.40 m$^3$ m$^{-3}$, which is below the water content at the mean field capacity; Table 4.6).
Lower moisture contents are typically increasing the penetration resistance (Hillel, 1998). The high clay content also contributes to a high penetration resistance. In the study of Cotching et al. (2001) on Vertisols with loamy clay to high clay content the penetration resistance increased to a mean value of 3.2 MPa at a depth of 60 cm. At the study location in the Mekong Delta, clay content was even higher compared to that study, resulting in an even higher penetration resistance (between 3 and 4 MPa at a depth of 60 cm). A penetration resistance above 2MPa would slow down root penetration drastically (Lowery and Morrison, 2002). Changing rice monoculture to crop rotation with one or two upland crops would improve the possibility of roots to penetrate.

4.2.6. Air capacity
Air capacity is an indicator of soil aeration, related to root-zone aeration, diffusion rates of gases and oxygen demands of soil fauna. AC is recommended to be ≥ 0.10 m³/m³ to avoid crop-damage because of aeration deficits in the root zone and ≥ 0.15 m³/m³ for fine textured soils (e.g. clayey soils), to compensate for low gas diffusion rates (Reynolds et al., 2007).

The results of AC for the different treatments and different depths are given in Figure 4.6. Only at depth 10-20 cm, the values of AC were significantly lower for R-R-R(+OM) than for R-Mb-R(+OM), R-Mb-R and R-Mb-M (22-34% lower). The other depths showed the same trends, but with a non-significant difference. The treatments with added organic manure also manifest a significant difference between the depths. These observations can be explained by the addition of organic manure at the upper depth, which results in an increased MacPOR (Table 4.4).
Chapter 4: Results and discussion

Figure 4.6: Air capacity of six different treatments at three depths. R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; AC, soil air capacity; Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; a, b, c are the significant differences between the rotations; the significant differences between the horizons has not been shown. Error bars represent the standard deviations.

All AC-values are lower than the recommended ones for good soil aeration (between 0.064 and 0.110 m³/m³). The low AC-values are possible due to the small amount of macro-pores, which were destroyed by the tillage in rice cultivation. These low values for AC account for the higher RWC values of the treatments because RWC was calculated inversely from AC (Table 4.6). For the rice cropping, AC is no good soil quality indicator because rice is cropped in flooded circumstances.

4.2.7. Aggregate stability

Soil aggregate stability is the ability of aggregates to resist mechanical and other disruptive forces. It is widely considered as a key indicator of soil quality and can be influenced by cropping systems, soil forming processes, soil texture, type of clay, organic matter and biological activity. Soil aggregates influence soil erosion, movement of water, soil compaction and root growth. In this study the stability quotient was used as a measure of structural stability (SQ; Table 4.5).

In the treatments with intensive rice cropping, SQ at depth 0-20 cm was significantly higher than at depth 20-30 cm. In R-R-R+OM the difference in SQ between the horizons is even more explicit, as the difference between SQ were also significant at 0-10 and 10-20 cm depth. R-R-R+OM had a significant higher SQ than the R-R-R treatment, at all depths. The addition of organic manure may explain an improvement in aggregate stability (Arthur et al., 2011; Khoa,
2002). This significant increase of SQ (22% at depth 0-10 cm, 17% at depth 10-20 cm and 10% at depth 10-30 cm) was also visible in R-M-R+OM in comparison with R-M-R.

The use of upland crops in the rotations showed a significant improvement in SQ compared to rice monoculture. When the rotations with the added organic manure are excluded, R-Mb-R showed the highest SQ, followed by R-M-R and R-Mb-M. R-Mb-M had a significant lower SQ at depth 20-30 cm, which is due to the lower OM-input in rotations with two upland crops.

In general, it can be concluded that the addition of organic manure and the rotation with upland crops improved aggregate stability.

Table 4.5: Influence of six different rotations of crops at three depths on selected soil physical quality indicators and parameters.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Horizon</th>
<th>SQ</th>
<th>S-index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-R-R</td>
<td>0-10 cm</td>
<td>109.62(12.78)(^d)_z</td>
<td>0.071(0.001)(^d)_z</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>100.36(13.21)(^d)_z</td>
<td>0.051(0.01)(^b)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>68.93(14.43)(^d)_y</td>
<td>0.034(0.01)(^a)_x</td>
</tr>
<tr>
<td>R-R-R+OM</td>
<td>0-10 cm</td>
<td>156.52(19.55)(^c)_z</td>
<td>0.076(0.001)(^c)_z</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>123.17(17.02)(^c)_y</td>
<td>0.063(0.01)(^a)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>87.69(5.62)(^c)_y</td>
<td>0.038(0.01)(^b)_x</td>
</tr>
<tr>
<td>R-M-R</td>
<td>0-10 cm</td>
<td>145.00(13.95)(^c)_y</td>
<td>0.070(0.02)(^c)_y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>143.29(15.50)(^c)_y</td>
<td>0.060(0.01)(^b)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>154.24(23.75)(^a)_y</td>
<td>0.060(0.01)(^a)_y</td>
</tr>
<tr>
<td>R-M-R+OM</td>
<td>0-10 cm</td>
<td>185.68(10.12)(^a)_y</td>
<td>0.063(0.01)(^a)_y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>173.09(10.66)(^a)_y</td>
<td>0.066(0.01)(^a)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>171.95(6.32)(^a)_y</td>
<td>0.070(0.02)(^a)_y</td>
</tr>
<tr>
<td>R-Mb-R</td>
<td>0-10 cm</td>
<td>173.25(16.63)(^b)_y</td>
<td>0.064(0.01)(^b)_y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>161.68(23.64)(^b)_y</td>
<td>0.063(0.001)(^b)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>160.49(21.84)(^a)_y</td>
<td>0.070(0.02)(^a)_y</td>
</tr>
<tr>
<td>R-Mb-M</td>
<td>0-10 cm</td>
<td>139.38(15.96)(^a)_y</td>
<td>0.070(0.01)(^a)_y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>151.55(7.02)(^a)_y</td>
<td>0.062(0.01)(^a)_y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>127.57(16.29)(^a)_y</td>
<td>0.065(0.001)(^a)_y</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; AC, soil air capacity; SQ, stability quotient; S-index, soil physical parameter index. Different letters in each column mean statistically significant differences at P ≤ 0.05 using DMRT; \(^a,b,c\) are the significant differences between the rotations; \(^x,y,z\) are the significant differences between the horizons. Numbers between brackets represent the standard deviations.
4.2.8. **Dexter’s physical soil quality index**

The S-index is related to the structural porosity of the soil. S-index ≥ 0.050 indicates “very good” soil physical or structural quality, while 0.035 ≤ S-index ≤ 0.050 is “good physical quality”, 0.020 ≤ S-index ≤ 0.035 is “poor physical quality”, and S-index ≤ 0.020 is “very poor” or “degraded” physical quality (Dexter, 2004a,b,c).

A significant decrease of the S-index, with depth, was observed in the R-R-R(+OM) treatments (50-52% decrease). All the other treatments showed no significant difference between the horizons. At depth 10-20 cm, the S-index of R-R-R was significantly lower (23-18% lower) than all treatments except for treatment R-M-R. For depth 20-30 cm, both rice monoculture treatments had a significantly lower (51-37% lower) S-index than all other treatments. The S-index was correlated with bulk density (r=0.70) and this explains the lower S-values for the rice monocultures at depth 20-30 cm. Similar to these findings, Reynolds et al. (2009) suggested a high correlation between these two soil quality indicators for all types of soil texture, except for some sandy soils.

R-R-R belonged with an S-index of 0.034 to the “poor physical quality” range. R-R-R+OM has a S-index of 0.038 at depth 20-30 cm, which is already “good physical quality”. All the other treatments were in the “very good physical quality” range. These values are exceptionally high for heavy clayey soils. Optimal S-values should be assessed for the function of the soil and crop. What might be bad for one crop, might be good for another, thus further research on the correlation between rice cultivation and S-index is designated before conclusions can be drawn. Dexter (2004a) suggested that the S-index decreases with clay content. He also suggested that for soils with a lower clay content OM is stronger correlated with the S-index. This explains the lower correlation (r=0.56) for the heavy clay soil from the study location.

4.3. **Soil water characteristics**

4.3.1. **Soil water retention curve**

The soil water retention curve represents the relationship between the soil matric potential and the water content of the soil. The curve is influenced by the total porosity, the pore size distribution, soil structure, soil texture and organic matter.

The van Genuchten equation (1980) was fitted to the observed data pairs to establish the curves shown in Figure 4.7 to Figure 4.9 for the different depths. The soil water retention curves showed steep slopes typical for clayey soils.
Chapter 4: Results and discussion

Some differences between the land use systems and management practices can be noticed in the curves and soil water properties have been calculated from the van Genuchten equation in order to compare the different treatments.

Figure 4.7: Effect of the treatments on soil water retention characteristics, at depth 0-10 cm.

Figure 4.8: Effect of the treatments on soil water retention characteristics, at depth 10-20 cm.
Figure 4.9: Effect of the treatments on soil water retention characteristics, at depth 20-30 cm.

4.3.2. Soil water properties

4.3.2.1. Soil water content at field capacity

The soil water content at field capacity is the maximum amount of water that a soil contains after free drainage. In the study location, it was not possible to determine the field capacity on site, and a soil water content at -33 kPa was used as an approximation (Θfc; Table 4.6).

In R-R-R and R-R-R+OM, Θfc increased significantly with depth (7% and 9% higher, respectively). Water content at field capacity also increased with depth in R-Mb-R (8% higher). This might be due to the higher MatPOR (Figure 4.2) at the upper horizon for these three treatments, because the water content at field capacity was chosen at -33 kPa. Macro-pores have been already drained at this matric potential and water retention is influenced mostly by matrix porosity.

In the upper horizon, only a significant higher Θfc was noticeable for R-Mb-M in comparison with R-M-R+OM. At depth 10-20 cm R-M-R(+OM) and R-Mb-R showed a significant lower Θfc than R-R-R(+OM) and R-Mb-M. R-Mb-M had a significantly lower (8-18% lower) Θfc than R-R-R+OM at depth 10-20 cm. At depth 20-30 cm the same trend was visible, although it was not significant. This can also be explained by the difference in MatPOR.
Chapter 4: Results and discussion

4.3.2.2. Soil water at permanent wilting point

The soil water at permanent wilting point (Θpwp; Table 4.6) is the residual water that is strongly held by the adhesive forces from the soil particles and is regarded as the lower limit of available water for plants. The volumetric soil water content at -15 bar was considered as a suitable working point of Θpwp (Romano and Santini, 2002).

The Θpwp of the rice monoculture treatments was significantly lower (22-30% lower) for the upper horizon. This can be explained by the higher amount of organic matter in the upper horizon that increases the amount of macro-pores and aggregates. For depth 0-10 cm, Θpwp was significantly lower for R-R-R+OM and R-M-R+OM, than for R-Mb-M (11 and 12% respectively). At depth 10-20 cm, a significant difference could be noticed: R-M-R(+OM) and R-Mb-R have lowest Θpwp, followed by R-R-R+OM and R-Mb-M, and highest Θpwp is for R-R-R.

For depth 20-30 almost the same trend can be noticed: R-R-R(+OM) showed the highest Θpwp (0.33-0.23 m³/m³), followed by R-Mb-M and R-Mb-R (0.27 and 0.26 m³/m³), and the lowest for R-M-R+OM (0.232 m³/m³). All these differences were strongly negative correlated with the OC-contents (r=0.84), leading to the conclusion that soils with high OC-content supply more easily water to the crops.
Chapter 4: Results and discussion

Table 4.6: Soil water characteristics for six different crop rotations at three depths.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>$\Theta_{fc}$ (m³/m³)</th>
<th>$\Theta_{pwp}$ (m³/m³)</th>
<th>RWC (m³/m³)</th>
<th>PAWC (m³/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-R-R</td>
<td>0-10 cm</td>
<td>0.452(0.03)aby</td>
<td>0.236(0.02)aby</td>
<td>0.832(0.02)y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.507(0.02)aby</td>
<td>0.301(0.01)y</td>
<td>0.879(0.03)y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.487(0.01)abc</td>
<td>0.329(0.02)y</td>
<td>0.860(0.02)y</td>
</tr>
<tr>
<td>R-R-R+OM</td>
<td>0-10 cm</td>
<td>0.457(0.001)aby</td>
<td>0.232(0.001)b</td>
<td>0.839(0.02)y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.514(0.02)aby</td>
<td>0.278(0.01)y</td>
<td>0.889(0.01)y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.504(0.01)aby</td>
<td>0.333(0.02)y</td>
<td>0.866(0.03)yz</td>
</tr>
<tr>
<td>R-M-R</td>
<td>0-10 cm</td>
<td>0.466(0.04)aby</td>
<td>0.245(0.01)aby</td>
<td>0.825(0.03)</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.436(0.03)c</td>
<td>0.244(0.02)c</td>
<td>0.817(0.04)b</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.446(0.04)c</td>
<td>0.246(0.01)bc</td>
<td>0.834(0.04)</td>
</tr>
<tr>
<td>R-M-R+OM</td>
<td>0-10 cm</td>
<td>0.434(0.04)b</td>
<td>0.230(0.01)b</td>
<td>0.797(0.04)</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.420(0.03)c</td>
<td>0.230(0.01)c</td>
<td>0.813(0.03)b</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.451(0.05)bc</td>
<td>0.232(0.01)c</td>
<td>0.852(0.05)</td>
</tr>
<tr>
<td>R-Mb-R</td>
<td>0-10 cm</td>
<td>0.453(0.02)aby</td>
<td>0.252(0.02)b</td>
<td>0.823(0.02)y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.436(0.02)c</td>
<td>0.236(0.01)c</td>
<td>0.820(0.02)y</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.491(0.02)abc</td>
<td>0.261(0.01)b</td>
<td>0.860(0.02)z</td>
</tr>
<tr>
<td>R-Mb-M</td>
<td>0-10 cm</td>
<td>0.497(0.03)a</td>
<td>0.260(0.02)b</td>
<td>0.828(0.02)y</td>
</tr>
<tr>
<td></td>
<td>10-20 cm</td>
<td>0.473(0.01)b</td>
<td>0.268(0.01)b</td>
<td>0.841(0.02)yz</td>
</tr>
<tr>
<td></td>
<td>20-30 cm</td>
<td>0.496(0.01)ab</td>
<td>0.266(0.02)b</td>
<td>0.867(0.02)z</td>
</tr>
</tbody>
</table>

R-R-R, rice-rice-rice rotation; R-R-R+OM, rice-rice-rice rotation+10 tons organic manure/crop season; R-M-R, rice-maize-rice rotation; R-M-R+OM, rice-maize (+10 tons organic manure)-rice; R-Mb-R, rice-mungbean-rice rotation; R-Mb-M, rice-mungbean-maize rotation; $\Theta_{fc}$, volumetric water content at field capacity; $\Theta_{pwp}$, volumetric water content at permanent wilting point; RWC, relative water capacity; PAWC, plant available water capacity. Different letters in each column mean statistically significant differences at $P \leq 0.05$ using DMRT; $a,b,c$ are the significant differences between the rotations; $x,y,z$ are the significant differences between the horizons. Numbers between brackets represent the standard deviations.

4.3.2.3. Relative water capacity

The relative water capacity (RWC; Table 4.6) represents the capacity of a soil to store water (and air) relative to the total pore volume. In the optimum range of RWC (0.6≤RWC≤0.7), the proportion of soil water and soil air maximizes microbial activity. For RWCs<0.6, the insufficient soil water reduces the microbial activity and for RWC>0.7 microbial activity will be reduced by insufficient soil air (Linn and Doran, 1984).

All of the RWC-values were higher than the optimum range, which could already have been expected from the low AC-values (Figure 4.6). The insufficient aeration could reduce microbial activity (Skopp et al., 1990). For horizon 10-20 cm, RWC was significantly higher for the rice monoculture treatments (4-9% higher), which results from the significant lower AC. R-M-R+OM at depth 0-10 cm scored best for RWC.
4.3.2.4. Plant available water capacity

For fine-textured soil, Cockcroft and Olssen (1997) recommended that plant available water capacity (PAWC; Table 4.6) should be higher than 0.20 m³/m³ to become maximum root growth and minimum susceptibility to ‘droughtiness’. Soils with a PAWC < 0.10-0.15 m³/m³ are ‘droughty’.

For both rice monoculture treatments PAWC decreased significant at depth 20-30 cm. This might be due to compaction at this depth, but in reality the rice fields are continuously flooded and its PAWC gives no important indication for rice cropping. For the upper horizon, no significant difference was observed, because Θfc and Θpwp follow the same trend. At depth 10-20 cm, R-R-R+OM had a significantly higher PAWC than all other treatments, which might be explained by its higher Θfc, due to the higher matrix porosity. For depth 20-30 cm, R-Mb-M and R-Mb-R showed significantly higher PAWC (23-31% higher) than the rice monoculture treatments. At this depth R-M-R(+OM) had also higher PAWC (22-27% higher), but not significant.

PAWC is not always the perfect measure to meet plant water supply. Easily available soil water is the fraction of PAWC that can be withdrawn without difficulties and the reduction of available soil water is regularly a consequence of intense evapotranspiration demands (Romano and Santini, 2002). To become the easily available soil water a depletion factor p should be used, which gives the average fraction of the total available soil water that can be depleted from the root zone before moisture stress. The value of p depends on the crop type, the crop development stage, soil texture and magnitude of evapotranspiration (Verplancke, 2003). For rice cultivation, no p-factor should be used because the field is flooded.

4.4. Field survey with farmers

Interviews with the local farmers at the study location and from surrounding areas with the same major soil group (Cai Lay district, Tien Giang province, Mekong Delta, Vietnam) were carried out to collect information about former and present land use system and land management practices. The investigation to a total of 109 farmers included four land uses: 30 farmers with 3 rice crops/year, 30 farmers with 1 rice and 2 upland crops/year, 30 farmers with 2 rice and 1 upland crop/year and 19 farmers with 3 upland crops/year.
4.4.1. History of land exploitation and land use

Local farmers exploited the land and produced one traditional rice crop per year before 1967. This traditional rice had a growing period of 5-6 months and yielded on average 2.5-3.0 tons/ha. Gradually, high yield rice varieties were introduced and two rice crops per year, a Winter - Spring crop and a Summer-Autumn crop were cultivated. Since 1980, three rice crops are cultivated: Winter - Spring rice (25-30/10 - 25-30/01), Spring - Summer rice (01-05/02 - 05-10/5), Summer - Autumn rice (15-20/5 - 01-05/9) with short growing periods of 90-100 days.

4.4.2. Present land use systems and cultivation practices

4.4.2.1. Planting practices

The farmers are used to sowing or transplanting the next crop when the previous one is harvested. The sowing density is 100 kg/ha – 200 kg/ha. The seeds are placed in water for 24 hours, they are kept warm for 36 hours and then sown directly on the field.

General crop schedule of the study location (Wet sowing)- 3 rice crop/year:

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<tr>
<th>Oct</th>
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</table>
| Crop 1: rice winter-spring | Crop 2: rice summer -autumn | Crop 3: rice Autumn - winter

General crop schedule of the study location - 2 rice crop+ 1 upland crop/year:

<table>
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<tr>
<th>Oct</th>
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</tbody>
</table>
| Crop 1 – rice winter-spring | Crop 2: upland crop summer -autumn | Crop 3 – rice Autumn - winter
Chapter 4: Results and discussion

**General crop schedule of the study location- 1 rice crop + 2 upland crops/year:**

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- **Crop 1:** rice winter-spring  
- **Crop 2:** upland crop summer-autumn  
- **Crop 3:** upland crop Autumn-winter

**General crop schedule of the study location- 3 upland crops/year:**

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</tbody>
</table>

- **Crop 1:** upland crop winter-spring  
- **Crop 2:** upland crop summer-autumn  
- **Crop 3:** upland crop Autumn-winter

4.4.2.2. *Rice variety*

The following rice (Oryza sativa) varieties are used OM 2517, OM 3536, OM 1490, OM 2514, OM 4495, IR 50404, MTL 250, MTL 233, VND 95-20.

4.4.2.3. *Land and crop management*

After harvesting the rice in the dry season (crop 1), the straw is broadcasted over the field and burned. After burning, the soil is irrigated and the flooded soil is puddled with a machinery-plough (tractor) or small handle tractor. Subsequently, the next crop can be sown.

After harvesting the rice in the rainy season (crop 2 and crop 3), the straw is cumulated in large bundles. Then, as a traditional land preparation before sowing, soil preparation is applied using a machinery-plough (tractor) or small handle tractor.

The soil is plowed 5-10 cm deep, three times per year for the three rice crops. For upland crop the soil is dug 20-30 cm deep and the farmer makes a raised bed.
4.4.2.4. Fertilization and crop protection

For the annual activities, the local farmer has to carry out some management activities for each rice crop cultivation:

- Fertilizer application: each rice crop is fertilized by rather high dose of NPK (examples of fertilizer: DAP, Urea, Superphosphat, Kaliclorua, NPK20-20-15, NPK16-16-8). Fertilizers are broadcasted by hand. Organic fertilizers are not applied.
- Crop protection (pesticides, insecticides, herbicides): Till, Validacine, Sofit, Basudin, Badan, Regent, Applaumic, Bassan,…
- Weed control and irrigation.

4.4.2.5. Soil management level

For soil improvement, no other activities are done besides the two main ones on the study location: ploughing and applying inorganic fertilizers.

4.4.3. Rice yield evolution

Based on the interviews with local farmers, the following information on crop yield was collected (Figure 4.10).

The rice yield is much higher for the Winter-Spring rice than for the Summer-Autumn or Autumn-Winter cropping period (Figure 4.10). This may be due to the better climatic conditions (Figure 3.3, period with average precipitation, Oct.-Jan.) and is the reason that rice is preferably cultivated in this period. According to the farmers, the main limiting factor for their crop production and income in the early growing period of the Summer-Autumn rice crop is water, accompanied by insect diseases and soil compaction.

In the last five years, the rice yield has been decreasing significantly for the intensive rice monoculture (decrease of 6%). For the crop rotation with one upland crop, the rice yield has significantly been increased over the last 5 years (8% increase for Autumn-Winter and 6% for Winter-Spring). For a crop rotation with two upland crops the rice yield has increased 7% over five years.
Figure 4.10: Rice yield within recent past 5 years (kg/ha) for different land management systems. 3xR, rice-rice-rice rotation; 2R+1xU, rice-upland crop-rice rotation; 1xR+2xU, rice-upland crop-upland crop rotation; W – Sp, Winter-Spring; Su – A, Summer-Autumn; A – W, Autumn-Winter.

4.4.4. Economic evaluation

In Figure 4.11, the costs for seeds and materials, fertilizers, pesticides and labor and the income have been visualized for the different land management practices.

The contribution of seeds and materials to the total cost is very low (5 to 7%) and the lowest for rice monoculture. Fertilizer application is 17 to 26% of the total cost. In rice monoculture more fertilizer has to be applied because of the unilateral use of the soil and its minerals. The rotation with one upland crop shows the lowest costs for pesticides. The interruption of the rice cultivation by an upland crop might break off the food-supply for rice specific pests and decreases need for pesticides. Pesticides are 10 to 12% of the total cost.

Labor manifests the highest contribution to the total cost (55-65% 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. The price for labor in comparison with rice monoculture is 40, 28 and 16% higher for three upland crops, two upland crops and one upland crop in the rotation, respectively. This makes the total cost to increase with increasing use of upland crops in the rotation.
The higher cost for labor has no economic consequence because the total income is also higher for rotations with more upland crops. However, the social impact of the land uses with upland crops is much higher. Farmers are reluctant to implement upland crops in their land use because the labor is high. This implies that cultivated fields have to be smaller to get the work done (this can be observed in Table 4.7). Moreover, young people are unwilling to work on the field and migrate to find employment in the cities so that workers in the field are scarce. Another reason for not implementing upland crops is the higher food-security of rice cultivation.

In Table 4.7 the average area under cultivation per farmer for the different land uses, which has been discussed earlier and the benefit-cost ratio is given. The benefit-cost ratio shows that rice monoculture has the lowest profit (49 to 52% lower than the other rotations) over costs and that a crop rotation with one upland crop is the most successful.
Chapter 4: Results and discussion

Table 4.7: Mean area under cultivation (ha) and costs-benefit ratio for different land management systems.

<table>
<thead>
<tr>
<th>Land use</th>
<th>3xR</th>
<th>2xR+1xU</th>
<th>1xR+2xU</th>
<th>3Xu</th>
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</thead>
<tbody>
<tr>
<td>Area (ha)</td>
<td>0.91(0.36)</td>
<td>0.68(0.33)</td>
<td>0.43(0.18)</td>
<td>0.36(0.15)</td>
</tr>
<tr>
<td>B/C</td>
<td>0.47</td>
<td>0.98</td>
<td>0.93</td>
<td>0.93</td>
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</table>

3xR, rice-rice-rice rotation; 2R+1xU, rice-upland crop-rice rotation; 1xR+2xU, rice-upland crop-upland crop rotation; Area, average area under cultivation per farmer (ha); B/C, benefit/cost-ratio; Numbers between brackets represent the standard deviations.

When the rice cropping was rotated with one or more upland crops, the rice yield reduction from the rice monoculture disappears and even an increase in rice yield has been observed. This changes are accompanied with a minor use of fertilizer and pesticides, and most important, an increase in farmer’s income.
5. GENERAL CONCLUSIONS AND RECOMMENDATIONS

Regarding the impact of land management on chemical parameters, this study showed that crop rotation with rice and upland crops in alluvial soils with a heavy clayey texture improves the distribution of OM and labile C between the horizons. For $N_{av}$ and $P_{av}$ this improvement has also been observed, but was less pronounced. The rotation with two upland crops showed a lower concentration of labile C, $N_{av}$ and $P_{av}$ in comparison with the rotation with one upland crop. This could be due to the high nutrient demand of upland crops and its low input of organic matter.

The type of land management also had an effect on physical soil properties. Rotations with upland crops showed a significant lower bulk density, higher total porosity and higher macro-porosity than rice monoculture with a compacted layer (20-30 cm depth). The rotation with two upland crops scores less good than the rotations with one upland crop for these parameters. The higher bulk density in the rice monoculture treatments causes a significantly increased soil strength or penetration resistance at the compacted layer, which makes it difficult for the crop roots to move within the soil. For the same reason, AC, SQ and the S-index are significant lower for the rice monoculture treatments. AC was lower than the optimum range for all treatments, and subsequently RWC was also higher than the optimum values. RWC was highest for rice monoculture treatments because of the flooded conditions. PAWC was also significantly lower for the rice monoculture cropping at the compacted depth, because of the higher bulk density.

The higher SOC-content in the rotations with one upland crop results in lower water content at permanent wilting point, compared to the other treatments. There is a high negative correlation ($r=0.84$) between SOC and water content at permanent wilting point, leading to the conclusion that soils with high OC-content supply more easily water to the crops.

The addition of organic manure to the rotations (R-R-R+OM and R-M-R+OM) did not show a significant increase in SOC and labile C and subsequently, no differences in bulk density and total porosity were observed. This might be due to the fact that organic manure has only been applied for four years, and progress might be possible in the future. Improvement in $N_{av}$, $P_{av}$ and TA has been observed due to addition of organic manure in the rice monoculture. PL, AC, SQ increase for both treatments with organic manure. A higher PL means that the topsoil becomes more stable with addition of organic manure. The increase of SQ gives a higher structural stability. The correlation of the S-index with SOC is quite low, and therefore the S-index does not impart a higher value for the treatments with added organic manure.
Chapter 5: General conclusions and recommendations

For matrix porosity, absence of optimum values makes it difficult to interpret the results. Anyhow, a higher MatPOR has been observed for the rice monoculture treatments because of the flooded conditions and for the rotation with two upland crops because of the aggregate breakdown by mixing. The matrix porosity influences the water content at field capacity because at field capacity macro-pores are already emptied. This is why the water content at field capacity was higher for the rice monoculture treatments.

From the interviews with the farmers, it was concluded that the rice yield was increased in the last five years when rotation with upland crops was implemented. This was strongly in contrast with the rice yield decrease over the last five years for rice monoculture. The use of upland crops in the rotation implies higher costs, especially for labor, and this makes that farmers are reluctant to use upland crops. The cost/benefit-ratio is the highest for rotation with one upland crop in between two rice cultivations.

From the above, it can be finally concluded that soil quality tends to improve with crop rotation, e.g. soil structure improves with cycles of drying (upland crops) and wetting (rice cultivation). In general, rotation with one upland crop and two rice cultivations gives a better soil quality and higher rice-yields than rice monoculture or rotation with two upland crops.

The advantage of higher soil quality and a higher cost-benefit ratio has to be balanced with the disadvantage of higher labor costs and the decline in food security. Farmers are reluctant to use upland crops for these reasons, and the recommendation of two upland crops in the rotation would be unrealistic.

In line with the findings of this study and the recognized gaps in knowledge, succeeding research should be investigating if soils that have been under rice monoculture show less optimal values for various parameters after one or more years of land use change and if long term effects of addition of organic manure on physical and chemical soil parameters give a different or higher contributions to soil quality.

The absence of an optimum range for matrix and macro-porosity makes it difficult to draw conclusions from these parameters. The optimal range of these soil quality indicators should be investigated and the relation between Dexter’s S-index and rice cultivation should also be researched to be able to conclude what is the good S-range for crop rotation involving rice and upland crops in clayey soils. To optimize the water content at field capacity in rice fields, a method to measure field capacity in the field of the rice cultivation should be developed.
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References


References


References


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Appendices

APPENDICES

A.1. Individual soil horizon description

Ap (0-20/25 cm): Distinguished by root distribution
This horizon is characterized by very dark grayish brown (10YR 3/2) at field conditions and gray (10YR 5/1) when dry. The soil texture is clay at this depth. It consists of many yellowish brown (10YR 5/6) spots, is massive, slightly sticky and plastic, and ripe. At this depth the soil has few open, tubular, bio-pores (0.5-1.0 mm) with many brown fresh fine roots. In the soil matrix are few spots of dark decomposed organic matter mixed. The boundary with the next horizon (AB) is clear and wavy.

AB (20/25-45/55 cm): Recognized by soil matrix color and soil mottling pattern
At this depth the soil is black (5Y 2.5/1) when moist and gray (2.5Y 5/1) when dried. The soil texture is clay. This horizon exists of 5-10 % brownish orange (2.5YR 3/6) and brown (7.5YR 4/4) and has distinct, clear fine mottles distributed mainly in soil matrix. The soil feels massive, sticky and plastic, and ripe. Few open bio-pores (<0.5 mm), few brown fresh roots and few traces of decomposed organic matter have been found. There is a clear and wavy boundary with horizon Bg1.

Bg1 (45/55-70/75 cm): Distinguished by soil matrix color and soil structure
Horizon Bg1 is gray (2.5Y 5/1) at field conditions, light gray (2.5Y 7/1) when dried. The soil texture is clayey. 15-20 % of the soil at this depth is strong brown (7.5YR 5/6) and possesses distinct, clear fine mottles distributed mainly in soil matrix. The soil feels moderate coarse, sub-angular blocky, slightly sticky and plastic and is ripe with common, open, fine and vertical channel bio-pores. The soil exists of very few, fine fresh roots and has a gradual, wavy boundary to Bg2.

Bg2 (70/75-130 cm): Justified by soil structure and mottling pattern
This depth of the soil is gray (2.5Y 6/1) at field conditions, light gray (5Y 7/1) when dry and the soil texture is clayey. 10-15 % of the horizon is reddish yellow (7.5YR 6/8) and distinct, clear fine mottles irregularly mixed in 2-4 % dark yellowish brown (10YR 3/4) are visible. Faint, diffuse mottles are distributed mainly in the soil matrix and on the surface of peds. The soil is weak, very coarse prismatic, slightly sticky and plastic, and nearly ripe. Common very fine channel bio-pores are present and a the horizon has a gradual, wavy boundary to Cg.
Cg (>130 cm): Recognized by soil matrix color and soil material
This depth is reddish gray (5YR 5/2) when soil is still wet, light brownish gray (10YR 6/2) when dry and the soil texture is sandy loam. The soil at this depth has no structure, is sticky and non-plastic, and half ripe. Common, soft, strong brown (7.5YR 3/4) and fine angular, manganese nodules are present in the soil matrix.