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Temporal changes of physical soil properties under different land use systems and land management practices of alluvial soil in the Mekong Delta, Vietnam

Titus Ghyselinck

Promoter: Prof. dr. ir. Wim Cornelis

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ABSTRACT

The Mekong Delta, situated in the South of Vietnam, is one of the largest and most fertile deltas in Southeast Asia. About 30% of the soils in the Mekong Delta are alluvial soils with a silt-clay to clayey structure, as they are formed from fine deposited material that is transported by the Mekong River. The delta is flat and the soils are poorly drained. The most important crop is rice. Due to the monocultural crop cultivation, imbalanced fertilizer application, changing land use and increasing mechanization, the land has degraded and consequently crop yields have decreased.

This research is a cooperation of Can Tho University, Vietnam and Ghent University, Belgium. A study area in Cai Lay district (Tien Giang province, situated in the Mekong Delta), where the alluvial soils have been used intensively for many generations is representative for the soils in the Mekong Delta. As for most fields, the area is suitable for rice production and therefore continuous rice cultivation is the dominant cropping pattern. For the experiment different land use and land management techniques – different crop rotations with or without use of organic fertilizer – are arranged on the test fields of the study area. The experimental site is arranged in a randomized complete block design with four replications for each land use system or treatment. The six different treatments are: rice-rice-rice, rice-rice-rice+10 tons of organic manure/crop season, rice-maize-rice, rice-maize (+10 tons of organic manure)-rice, rice-mungbean-rice and rice-mungbean-maize.

Former research performed on the test field has indicated that soil quality and crop yields were improved by introducing upland crops and thus a more diverse crop cultivation pattern. This part of the research focuses on the soil physical characteristics of the soil and examines presence and effect of temporal variability of these soil physical parameters. The soil physical parameters for which temporal variability was examined are bulk density, soil porosity, matrix- and macroporosity, infiltration rate and field saturated hydraulic conductivity. Spatial variability of soil physical parameters has long been observed, but soil physical parameters have generally been assumed to be constant in time. Insight in temporal variability improves the understanding of soil physical properties and can be included in models. Models allow us to perform research in a fast and efficient way in order to improve cultivation techniques and investigate new methods for a better, more efficient and sustainable form of agriculture.

Results showed differences in soil physical characteristics as an effect of crop rotation system. These differences are linked with depth. Results showed that for the monoculture rice treatments, values of bulk density were significantly greater and matrix/macro porosity values were significantly lower at the 10-20 cm and 20-30 cm horizon, compared to the treatments where upland crops are introduced.

Result showed that in some cases time is a significant factor of variability in soil physical parameters. Seasonal temporal variability for the factors bulk density, matrix- and macroporosity was especially observed for those treatments where the management consists of a rice monoculture. The results for infiltration rate and field saturated hydraulic conductivity showed great temporal variability, both seasonal and interseasonal. Interseasonal variability was most pronounced for the treatments where rice is cultivated in the winter-spring season and upland crops during summer-autumn season. Seasonal

variability was present for rice monocultures in both seasons but strongest variability was found for the rice-upland crop rotations during the summer-autumn season.

The effect of temporal variability was examined for the FAO crop model AquaCrop. Temporal variation in hydraulic conductivity and saturated water content was considered for the simulation and description of biomass, canopy cover and soil water content for the representative fields. Simulation results showed that temporal variability of these parameters has a significant effect on the goodness-of-fit of the simulation results for soil water content. The effect on and canopy cover and biomass of rice was limited since water stress did not occur. These findings indicate that the effect of temporal variability should not be neglected and introduction of temporal variability may lead to a more accurate result of modeling.

SAMENVATTING

De Mekong Delta, gesitueerd in het zuiden van Vietnam, is een van de grootste en meest vruchtbare delta's in Zuidoost Azië. Ongeveer 30% van de bodems in de Mekong Delta zijn alluviale bodems met een lemig klei tot kleitextuur, aangezien ze gevormd zijn door depositie materiaal dat door de Mekong wordt getransporteerd. De delta is vlak en slecht gedraineerd. Het belangrijkste gewas is rijst. Door de gewas cultivatie in monocultuur, onevenwichtige bemesting, veranderingen in land gebruik en stijgende mechanisatie is het land gedegradeerd en zijn bijgevolg de gewasopbrengsten gedaald.

Dit onderzoek is een samenwerking tussen Can Tho University, Vietnam en Universiteit Gent, België. Een studiegebied in Cai Lay district (Tien Giang provincie, gesitueerd in de Mekong Delta), waar alluviale bodems reeds vele generaties intensief zijn gebruikt is representatief voor de bodems in de Mekong Delta. Zoals voor de meeste velden het geval is, is het gebied geschikt voor rijstproductie waardoor een continue rijstteelt de gangbare landbouwactiviteit is. Voor het experiment zijn verschillende landgebruiken en landbeheersvormen – verschillende gewasrotaties met of zonder gebruik van organische bemesting – gerangschikt in een gerandomiseerd complete blok ontwerp met vier herhalingen voor elk landgebruik systeem of behandeling. The zes verschillende behandelingen zijn: 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.

Eerder onderzoek uitgeoefend op het test veld heeft aangewezen dat de bodemkwaliteit en gewasopbrengst verbeterd waren bij de velden waar één niet-rijst gewas werd geïntroduceerd en bijgevolg een meer diverse gewasteelt voorkwam. Dit gedeelte van het onderzoek gaat het voorkomen en effect na van temporele variabiliteit van de bodemfysische parameters. Deze bodemfysische parameters waarvoor temporele variabiliteit werd onderzocht zijn bulk densiteit, bodem porositeit, matrix- en macroporositeit, infiltratiesnelheid en veld gesatureerde hydraulische conductiviteit. Ruimtelijke variabiliteit van bodemfysische parameters is reeds lang geobserveerd, maar over het algemeen werd verondersteld dat de bodemfysische parameters constant zijn over de tijd. Inzicht in de temporele variabiliteit verbeterd het inzicht van bodemfysische eigenschappen en kan in modellen inbegrepen worden. modellen laten ons toe om onderzoek uit te voeren op een snelle en efficiënte wijze zodat teelt technieken verbeterd kunnen worden en nieuwe methoden onderzocht kunnen worden voor een betere, efficiëntere en meer duurzame manier van landbouw.

De resultaten toonden verschillen in bodemfysische eigenschappen als gevolg van het gewasrotatie systeem. Deze verschillen zijn gekoppeld met de diepte. De resultaten toonden dat voor de monocultuur rijstbehandelingen, de waarden voor bulk densiteit significant groter en de waarden voor matrix/macro porositeit significant kleiner waren voor de 10-20 cm en 20-30 cm horizont, in vergelijking met de behandelingen waar niet-rijst gewassen geïntroduceerd werden.

De resultaten toonden dat de factor tijd in sommige gevallen weldegelijk een significante factor is voor de variabiliteit van bodemfysische parameters. Seizoenale temporele variabiliteit voor de factoren bulk densiteit, matrix- en macroporositeit werd voornamelijk geobserveerd bij deze behandelingen waar het beheer bestaat uit een monocultuur rijstteelt. De resultaten voor infiltratie snelheid en veld gesatureerde hydraulische geleidbaarheid vertoonden grote temporele variabiliteit, zowel seizoenaal als interseizoenaal. Interseizoenale variabiliteit was het sterkst uitgesproken voor de behandelingen waarbij rijst wordt gecultiveerd gedurende het winter-lente seizoen en een niet-rijst gewas gedurende het zomer-herfst seizoen. Seizoenale variabiliteit was aanwezig voor de rijst monoculturen gedurende beide seizoenen maar de sterkste variabiliteit was gevonden voor de rotaties met een niet-rijst gewas, gedurende het zomer-herfst seizoen.

Het effect van temporele variabiliteit was onderzocht voor het FAO gewas model AquaCrop. Temporele variabiliteit in hydraulische geleidbaarheid en verzadigde water gehalte werd beschouwd voor de simulatie en beschrijving van biomassa, gewasbedekking en bodem water gehalte voor de representatieve velden. De simulatieresultaten toonden dat temporele variabiliteit van deze parameters een significant effect hebben op de overeenkomst van de simulatieresultaten en werkelijke waarden voor vochtgehalte. Het effect op biomassa van rijst was gelimiteerd aangezien water stress niet optrad. Deze bevindingen tonen aan dat het effect van temporele variabiliteit niet mag genegeerd worden en dat de introductie van temporele variabiliteit kan leiden tot een preciezer resultaat van modellering.

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LIST OF ABBREVIATIONS AND ACCRONYMS

ANOVA	Analysis of Variance
ASEAN	Association of South-East Asian Nations
B	Total aboveground biomass production
BD	Bulk density
CC	Canopy Cover
CC_0	Initial canopy cover at 90% crop emergence
CC_x	Maximum canopy cover
CDC	Canopy decline coefficient
CEC	Cation Exchange Capacity
CGC	Canopy growth coefficient
CIMMYT	International Maize and Wheat Improvement Center
d	Willmott's index of agreement
DAS	Days After Sowing
DMRT	Duncan's Multiple Range Test
D_r	Root zone depletion
E	Soil evaporation
e_a	Actual vapor pressure
EC	European Commission
EF	Nash-Sutcliffe model efficiency coefficient
e_s	Saturated vapor pressure
ET	Evapotranspiration
ET_0	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations

G	Soil heat flux density
GDP	Gross Domestic Product
GSO	General Statistic Office (Viet Nam)
HI	Harvest Index
HI_0	Reference Harvest Index
I	Infiltration rate
i	Cumulative infiltration
IOF	Inorganic fertilizer
K	Hydraulic conductivity
Kcb	Crop transpiration coefficient
Ke	Soil water evapotranspiration coefficient
K_{fs}	Field-saturated hydraulic conductivity
Ks	Water stress coefficient
Ksat	saturated hydraulic conductivity
LAI	Leaf Area Index
MacPOR	Macroporosity
MatPOR	Matrix porosity
MARD	Ministry of Agriculture and Rural Development
MIRA	Milieurapport Vlaanderen
NMRSE	Normalized Root Mean Square Error
OM	Organic Manure/fertilizer
p	Depletion factor
R^2	Coefficient of determination
RH	Relative Humidity
R_n	Net radiation at crop surface
RMSE	Root Mean Square Error

SA	Summer Autumn season
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
T	Treatment
TAW	Total Available Water
Tmax	Maximum temperature
Tmean	Mean temperature
Tmin	Minimum temperature
Tr	Crop transpiration
u_2	Wind speed at 2 m
UNEP	United Nations Environment Programme
USDA	United Stated Department of Agriculture
W_r	Soil water content of the root zone
WP	Crop water productivity
WP*	Normalized crop water productivity
WS	Winter Spring season
Y	Yield
Z	Effective rooting depth
α^*	Soil macroscopic capillary length parameter
θ	Volumetric water content in the root zone
θ_{FC}	Volumetric water content in the root zone at field capacity
θ_{PWP}	Volumetric water content in the root zone at permanent wilting point
Δ	Slope of the vapor pressure curve
γ	Psychometric constant

1. INTRODUCTION

Serving as a staple food for about half of the world's population, rice is considered as one of the world's most important crops in terms of food supply. With the continuous growth of the world's population – and hence the rice consuming population – a further increase in the demand for rice is expected (Sawano *et al.*, 2008) while the total area available for cultivation is decreasing due to urbanization and other causes such as land degradation. On top of this, climate change, which can no longer be neglected, may have serious direct and indirect consequences for rice production and hence food security (Jalota *et al.*, 2012). For example, sea level rise as a result of climate change causes flooding of land and thus a loss of total and agricultural land area. Another effect of inland transgression of the sea is salt intrusions into the soil, compromising the availability of fresh water for crops and making the land unsuitable for agriculture.

These two processes of increase in food requirement due to a worldwide population growth and a possible decrease in overall production due to threats by climate change and land degradation processes, make it important to create a system able to support optimal crop growth and food supply. In Southeast Asia, one of the most important regions for rice production, sustainability of rice is of great concern from the viewpoint of food security of the continuously increasing population and livelihood of farmers (Jalota *et al.*, 2012).

In recent years, rice production has known a strong development in terms of area, productivity and output. However, the potential for further expansion of rice production is limited. A part of the agricultural land is absorbed by urban and industrial development and an increasing share of the land is being allocated to aquaculture, vegetables and other crops as farmers diversify production to meet the demands of urban consumers (MARD, 2002). This results in a decrease of the area available for rice production. Increase in productivity and intensification of rice production is thus needed to compensate this loss in rice-growing area.

This, however, is not easy. Intensification of agricultural practices is strongly dependent on – and thus limited by – the capacity of the land and the soil to support crop production. Soil is a non-renewable resource and it is thus important to maintain its quality, in order to support food production and other services for present and future generations. Therefore, a more sustainable use of the soil is needed, allowing the possibility to fulfill the needs of the growing world population without degrading the land, and more specifically the soil from which the farmers are depending.

The alluvial soils of the Mekong Delta are very suitable for rice production and has been intensively used by generations of farmers, primarily for rice cultivation (Khoa, 2002). The intensive land use involves the growth of three rice crops per year and sometimes up to seven crops in two years. Over the years practices such as irrigation, drainage, tillage under wet conditions, use of inorganic fertilizer and others have been performed on these soils, causing a degradation of the land. As an effect of this intensive use and land degradation rice yields have been declining every year, even with the use of the same or increased amounts of fertilizers. Experiments have been set up, using new land management techniques implementing rotation of rice and upland crops (maize and mungbean) in order to improve soil quality and fertility (Tran Ba Linh *et al.*, 2013). Besides the improvement of soil quality, the implementation of upland crops in a rice crop rotation allows the farmers to grow and offer a higher diversity in products.

Several studies have investigated the effect of agricultural and soil management practices on soil properties, in order to evaluate soil quality towards crop productivity and food security. Traditionally, soil samples are taken or field measurements conducted at one given instant within the growing season. However, recent studies have demonstrated that particularly physical soil properties are changing with time within a growing season, depending on the soil type, climate conditions, and agricultural and soil management practices (Strudley *et al.*, 2008). When evaluating the effect of different management practices on the soil quality, it is thus important to include the temporal effect. Moreover, Mubarak *et al.* (2009) demonstrated that when considering temporal variation in modeling water flow, irrigation efficiency could be improved.

The objectives of this research were therefore to (1) better understand the effect of different agricultural uses and management practices on selected soil physical properties, (2) how these properties change with time, and (3) how this might affect the predicted biomass and yield of rice grown in the Mekong Delta, Vietnam with a cropwater model (AquaCrop; Steduto *et al*., 2009)

2. LITERATURE REVIEW

2.1. Study area

Nowadays, one of the leading countries responsible for rice production and supply worldwide is Vietnam. The country has experienced enormous progress, evolving from being a rice importer to a net rice exporter. Vietnam is the second largest rice exporter in the world since 1995. In recent years, the annual volume of rice exports has grown considerably. With annual rice exports reaching over 3.5 million tons, the country represents a share of about 16% of the world rice market (UNEP, 2005).

The country of Vietnam (Viet Nam, Figure 2.1) is situated in the centre of Southeast Asia, on the eastern side of the Indochina Peninsula. The country is stretched out from south to north, with a long coastline along the South-Chinese Sea. Because of this strong variability in longitude the climate is strongly variable. There is a tropical climate in the south and a monsoonal climate in the north. Two seasons are distinguished: a hot rainy season from May to September and a warm, dry season from October to March (Index Mundi, 2012). The considered area of the Mekong delta is situated in the southern part of Vietnam (indicated in the box on Figure 2.1).

Figure 2.1: Map of Vietnam, with indication of the Mekong delta

The Mekong Delta is considered to be one of the largest, most fertile deltas in Southeast Asia, ideal for the cultivation of rice. The Delta is formed by the Mekong River, which originates in the Tibetan Highland and flows over a length of more than 4500 m and flows into the South-Chinese Sea. At the coastal areas, where the river flows into the sea, the water flow is much slower, allowing settlement of the sediments and sludge that are transported by the river. This process has been going for over millions of years, creating a vast, fertile plain of fine materials and sludge. This sludge is a product of erosion causing the fine clayey soil particles to run off the land, into the river, which is nowadays still ongoing. Consequently, each year the delta grows 50 to 100 m into the South-Chinese Sea and Gulf of Thailand. Water from the

Mekong River is the main water resource of the Delta. It is used for fishing, irrigation and domestic purposes (Minh, 2000).

About 30% of the soils in the Mekong delta are alluvial soils and consist of a loamy or clayey texture. The south of Vietnam has a tropical monsoon climate (ASEAN Regional Centre for Biodiversity Conservation, 2012) with temperatures varying from 25°C to 30°C. There are two seasons: the rainy season from May to October and the dry season from December to April. The annual rainfall for Can Tho, the central town of the Vietnamese Mekong and closest to the study area is about 1630 mm (Worldbank, 2013). This high precipitation amount meets the high water requirements needed for rice production, making the region ideal for rice cultivation.

Due to its high fertility and availability of water from rainfall and coming from the Mekong River, the delta forms an ideal environment for rice agriculture. Due to its agricultural value, the delta region is of high importance for the economic welfare of the Vietnamese people leading to a densely populated area.

Almost half of the agricultural land in Vietnam is allocated to paddy rice. The total area under rice is about 7.5 million hectares. More than 90% of the agricultural land, allocated to rice production, is situated in the country's two major deltas, the Red River Delta and the Mekong River Delta. More than 94% of the rice-growing land area is allocated to individual households. Most farmers plant rice primarily to meet their food demands but it is also the main source of income for rural households (44 to 51% of household revenue). Rice is the number one export product for Vietnam. Over the past ten years, Vietnam has become one of the largest rice exporting countries in the world. An average of 3.5 million tons of milled rice is exported each year. It is the most important crop in the agricultural sector and it is difficult to overstate the importance of rice to the Vietnamese economy. About 80% of the population grows rice and almost half of these produce a surplus that is used for sale (UNEP, 2005).

Together with Thailand, Vietnam is one of the leading countries in the export of rice. In 2000, Vietnam's share in the world rice market was about 16%. The growth in rice production and rice exports has brought, among other effects, an increase in agricultural income and GDP, and has had a positive impact on poverty reduction. However, the policies promoting rice production and trade have also had a number of negative environmental and social impacts, such as adverse effects on human health from the misuse of fertilizers and pesticides, environmental degradation and loss of rice biodiversity from technology inputs. Rice continues to play a central role in Vietnamese agricultural production and food consumption (GSO, 2001).

As a result of the higher rice demand and increasing need for income, farmers practice rice intensification and increased rice cropping. Two rice crops per year is the common practice for irrigated rice. Even three rice crops per year are cultivated, although the Vietnamese Agricultural Department no longer recommends this cropping practice because the risks from natural disasters or pest infestation seem to be increasing and the quality of the soils is decreasing more rapidly (GSO, 2002).

The second most important food crop in Vietnam is maize. It is used as a substitute staple in periods of rice shortage. It is also the primary source of feed for Vietnam's poultry and livestock industry, and is therefore an important source of income for many farmers (CIMMYT, 2004). Maize production has risen sharply since 1990, from 431,800 ha yielding an average of 1.6 $ton.ha^{-1}$ and a total production of 671,000 ton to a total planted area of 659,000 ha yielding an average of 2.5 $ton.ha^{-1}$ in 1999 (GSO, 2001). This dramatic change in maize demand and production has made a significant positive economic to many rural areas in Vietnam. Economic growth and urbanization in Vietnam are expected to create an even higher demand for maize, leading to an intensification of current maize production systems, with more land being allocated to maize production. Maize is particularly grown in the upland areas. Compared to these upland areas, only little maize is grown in the flat wetlands of the Mekong Delta and contributes little to the total farm income. However, some maize is grown in the winter-spring dry season after two successive rice crops (CIMMYT, 2004).

The government of Vietnam acknowledged many years ago the importance of grain legumes, such as soybean and mungbean, their role as a human food, animal feed and their beneficial effect for the soil. After rice and maize, soybean was the third priority for upland crop research in Vietnam in 1995. Generally, farmers prefer to grow high-yielding cereals like maize and rice, particularly if fertilizer nitrogen is readily available and relatively inexpensive. However, soybean and mungbean may still provide an economic alternative to at least some of the cereal production (e.g. Dong Nai province in southeastern Vietnam), provided that they are high yielding and robust in terms of pest and disease resistance (Tien *et al.*, 2002).

2.2. Soil: introduction

Soil is a non-renewable natural resource fulfilling some crucial ecological, economic and social functions. It is the upper part of the earth crust and the essential component of the terrestrial environment. It forms the interface between geosphere, atmosphere, hydrosphere and biosphere. The soil can sustain in plant and animal productivity, maintain or enhance water and air quality and support human health and habitation. The soil consists of a solid phase and a pore phase. The solid phase is formed by mineral and organic material. The pores are filled with water and air in a variable ratio (Doran and Parkin, 1994).

The soil characteristics are determined by a number of properties. The proportions of sand, clay and loam (texture), organic matter and mineral components, and water and air (in the pore space) and the way these form a stable structure are the most important. A soil consists of different horizons with different chemical, physical and biological properties (Wild, 2003).

The soil has several important functions in the environment. These functions include 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 archaeological heritages. These functions are determined by the soil characteristics, which makes knowledge about the physical, chemical and biological processes and their interactions very important (Hassett and Banwart, 1992; Tóth *et al.*, 2007).

Soil formation is determinant for the soil structure and its characteristics. It is a slow process in which the parent material is modified due to the influence of external factors. The most important factors influencing soil formation are parent material, relief, climate, time and biological factors (vegetation, soil fauna and humans). Soil is said to be a non-renewable resource due to the fact that soil formation and recovery are time-consuming processes (MIRA, 2011).

2.3. Alluvial soils

Alluvial soils are relatively young (less developed) soils and can be found in alluvial plains (Edelman and Van der Voorde, 1963). They are fine-textured soils with a dominantly silt-clay to clay texture (Tran Ba, 2004). Soils of alluvial plains are formed from various materials deposited by fluvial and/or colluvial processes at flat or nearly flat areas. The driving forces of this deposition are water flow and gravity. Formation processes lead to variability in physical, chemical and mineralogical properties resulting from differences in mineral composition, origin of the sedimentary material and deposition of soil. The formation processes also lead to accumulation of nutrients. The supplied sediment in the Mekong River is rich in nutrients because of its excessive basins. The high nutrient richness makes alluvial soils often more productive than the soils in uplands (Brubaker, 1993). Alluvial soils are worldwide responsible for more than 25% of food supply (Gerrard, 1987).

The Mekong Delta has a total of one million ha of alluvial soils (Khoa, 2002), equal to 31.5% of the delta's total land area (Chieu et al., 1990; Ve and Anh, 1990). The amount of water that is transported annually by the Mekong River is 500 billion m^3, containing 70 million tons of sludge. Every year, during the flood season, sedimentation of the sludge occurs. The alluvial soils are the best soils in the Mekong Delta for agronomical purposes.

The fertility of an alluvial soil is dependent on the type of clay mineral that is deposited. In the tropics the most important clay minerals are kaolinite, illite (by contact with seawater) and montmorillonite. The physical fertility of a soil is mostly determined by its structure and its swell-shrink capacity (Brady, 1998).

2.4. Puddled soils

To reduce water, nutrient and weed stresses, rice (*Oryza sativa*) needs to be grown under continuous submerged conditions. Ideal to maintain these conditions are impermeable or puddled soils (Kirchhof and So, 2005). Wet cultivation or soil puddling is the most common soil preparation technique used to support lowland rice production (Sharma and De Datta, 1985). With puddling, soil aggregates are smeared, broken down and dispersed (Pasaribu and McIntosh, 1985). Destruction of soil aggregates reduces percolation losses, thereby, decreasing the proportion of transmission pores and hydraulic conductivity (Prihar *et al.*, 1976). The degree to which these processes occur is usually affected by the soil type and structure, and the intensity of puddling. Reduction of hydraulic conductivity is necessary for the decrease of water and nutrient losses. As an effect of the continuous submerged conditions of the field during the rice cropping cycle, weed growth is limited and almost absent (Sharma and De Datta, 1985).

Farmers puddle their paddy fields to reduce percolation losses during transplanting. Therefore, after long cultivation periods, a 5 to 10 cm plow sole layer (or hard pan) is formed at a depth of 20 to 30 cm below the ground surface. This layer prevents the infiltrated ponded water from drainage further downward in the soil (Liu et al, 2001).

Puddling of a soil is generally believed to be more beneficial for rainfed rice production, because it improves the water retention capacity of soils. Under water stress condition, puddled soil is found to be more supportive for rice crop production than non-puddled soil (De Datta and Karim, 1974; Mambani *et al.*, 1990). However, after the rice season, the puddle layer has a tendency to dry out, resulting in adverse soil conditions for the crops that are grown on this soil during the dry season (Pasaribu and McIntosh, 1985).

2.5. Soil Quality

Soil quality is what can be described as the condition of a specific soil to function for a specific use. The simplest definition to describe soil quality is "the capacity of a soil to function" (Pierce and Larson, 1993; Karlen *et al.*, 1997). A more extended definition gives a more detailed overview on the context of soil quality. This definition states soil quality as: "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain biological productivity, maintain or enhance environmental quality, and promote plant, animal and human health and habitation" (Doran and Parkin, 1994; Karlen et al, 1997).

Soil quality is considered to be the total of chemical, physical and biological properties and processes of soil and its surroundings. The meaning of soil quality is dependent on the spatial scale at which it is evaluated and also on the interest of use of the soil for the evaluator. Agricultural soils do not solely have to support crop and animal growth but have other important functionalities. In order to maintain, recover or improve the quality of a certain soil, it is important to know which functions this soil has to fulfil (Karlen *et al.*, 1997; EC, 2002; Cuijpers *et al.*, 2008; Reubens *et al.*, 2010). As recommended by Doran *et al.* (1996), soil quality should rather be based on its function. Soils that are not suitable for e.g. agricultural use should therefore not be described as bad quality soils as they might be suitable for a different use. The quality of a soil should thus be described relative to the purpose for which the soil is used. It is generally not possible to find a perfect combination between a soil and its function, in which case a best management scenario is recommended. Although soil quality defines an objective state or condition of a soil, it has to be seen subjectively because the evaluation of soil quality is dependent on personal and social determination (Carter, 2002). An agricultural soil with good quality possesses the physical, chemical and biological attributes which make the soil able to promote and sustain good agricultural productivity without compromising the health of the environmental. A soil with poor quality is a soil that may not possess some or all of the attributes required for agricultural productivity, or does not ensure a negligible environmental impact and degradation (Reynolds *et al.*, 2007).

Soil quality can be subdivided in the soil's inherent capacity to support plant growth and in a dynamic part that is influenced by the user of the soil. Dynamic soil quality contains these soil properties that are changing in a short time period and that are influenced by human activity like agronomic land practises. In this way it can be said that optimal quality is achieved when the soil operates at its full potential, for a specific land use (Karlen *et al.*, 1997). Inherent soil quality is the total of a soil's natural composition, the function of soil state factors and the geological materials of a soil. Unlike dynamic soil quality, the factors describing inherent soil quality are almost static and change little over time.

Besides intrinsic soil factors, it is also important to consider extrinsic factors such as climate, topographic and hydraulic parameters to evaluate inherent soil quality for crop production. For example, strong water retention of clayey soils is beneficial in dry, (semi)arid areas but not desirable in humid conditions with poorly drained areas. For this reason it is not possible to work out a universal set of inherent soil criteria (Carter, 2002). It also implies that the system will be truly sustainable if ecosystem processes are well understood (Karlen et al, 1997; Carter, 2002). Improvement of ecosystem management and soil interpretation can be obtained with an evaluation of the relationship between the inherent and the dynamic properties (Levi *et al.*, 2009).

There is no way to directly measure soil quality, but soil properties that are sensitive to changes in management can be used as indicators (Andrews and Cambardella, 2004; Reynolds *et al.*, 2007). However, these indicators are variable according to the location, and the level of sophistication at which measurements are likely to be made (Riley, 2001). Therefore, it is not possible to develop a single short list, suitable for all purposes. Also, the use of a range of likely indicators is preferred rather than a single indicator (Syers at al., 1995).

2.6. Soil physical quality

Due to the high complexity of the soil environment, agricultural soil quality can be divided in three components: soil physical quality, soil chemical quality and soil biological quality (Dexter, 2004). These three components interact strongly and are thus not truly separable.

Soil physical quality can be linked with to the soil's strength and its fluid transmission and storage characteristics in the crop root zone. This in turn is the result of soil physical properties such as texture, structure and hydraulic properties, climate, management practices, crop types, and various soil-based chemical and biological processes (e.g. oxidation-reduction, mineralization, faunal activity) (Topp *et al.*, 1997).

Generally speaking, a soil with "good physical quality" has indicator values within the optimal ranges, or at least not beyond the critical limits (Arshad and Martin, 2002). An agricultural soil that is classified with good physical quality is a soil that is strong enough to maintain good structure to support standing field crops, but also weak enough to allow optimal proliferation of crop roots, soil flora, and soil fauna. A soil with good physical quality has the ability to store and transmit water, air, nutrients and agrochemicals in a way that it promotes both maximum crop performance and minimum environmental degradation (Topp *et al.*, 1997).

Soil physical quality is relevant and important for the entire crop rooting zone, which is dependent on the crop, but can be generally considered to be the top 100 cm of the soil profile. The top 10 cm, however, is particularly important because it controls many critical agronomic and environmental processes. Seed germination and early growth, aggregation, land practises (e.g. tillage, fertilization), erosion, runoff and infiltration are some important processes that are mainly set in the top 10 cm. In addition, the majority of soil physical responses to livestock treating, cropping and tillage seem to occur in the top 5-15 cm of the soil profile (Drewry, 2006).

Despite great efforts over the last decades, a coherent and formalized set of soil physical quality indicators has not yet been developed (Arshad and Martin, 2002). In addition, optimum and critical values or ranges for most soil physical indicators are still unknown or undefined (Arshad and Martin, 2002). Nevertheless various guidelines have been proposed for both agricultural and non-agricultural soils (Hall *et al.*, 1977; Greenland, 1981; Carter, 1990; Craul, 1999; Reynolds *et al.*, 2002; Drewry and Paton, 2005). It is becoming clear that bulk density, permeability, and various forms of porosity, aeration and water retention will be key components of the set of parameter indicating soil physical quality. Work by Hall *et al.* (1977), Greenland (1981), Carter (1990), de Witt and McQueen (1992), Reynolds *et al.* (2002, 2007, 2008, 2009), Drewry and Paton (2005) and others suggests that for medium to fine textured agricultural soils, bulk density, hydraulic conductivity, and various air and water capacity relationships are commonly used indicators for the soil's physical quality with respect to soil strength, soil water transmission, and soil air–water storage, respectively. In addition, soil organic carbon content is known to be a critical parameter affecting virtually all aspects of soil physical quality (Gregorich *et al.*, 1997; Shukla *et al.*, 2006).

The optimal indicator ranges and critical limits for agricultural soils have traditionally been generalized to broad soil types. Olness *et al.* (1998) suggest that in “medium–fine textured” agricultural soils, optimal bulk density is found in a range of 0.9–1.2 $Mg.m^{-3}$. Research by Khoa (2002) describes that for the Mekong Delta, rice yields are negatively influenced by a soil bulk density of 1.35 $Mg.m^{-3}$. Soil bulk density greater than 1.40 $Mg.m^{-3}$ is considered as a limiting boundary for agricultural production in mineral soils (Lal and Steward, 1990).

The saturated hydraulic conductivity (Ksat) of a soil is an important indicator of the soil’s ability for absorption, transmission and drainage of water (Topp *et al.*, 1997). Ksat values for the root zone within the range of $5x10^{-5}$ $m.s^{-1}$ to $5x10^{-6}$ $m.s^{-1}$, can be considered as ideal for a rapid infiltration and redistribution of needed crop-available water, reduction of surface runoff and soil erosion, and encouraging rapid drainage of excess soil water (Reynolds *et al.*, 2003). de Witt and McQueen (1992) and McQueen and Shepherd (2002) proposed a lower critical limit for Ksat for fine textured agricultural soils of $1.0x10^{-6}$ $m.s^{-1}$. Below this value, crop production is frequently and substantially hindered due to inadequate root-zone aeration, reduced trafficability, and increased surface runoff and erosion. An upper critical limit has not yet been proposed, but a value of Ksat = $1.0x10^{-4}$ $m.s^{-1}$ may be a reasonable limit as soils defined as ‘droughty’ often have Ksat > 10^{-4} $m.s^{-1}$ due to coarse texture or excessive cracks and biopores (Marshall and Holmes, 1988; Topp *et al.*, 1997).

2.7. Soil degradation: processes

Soil degradation can be defined as the loss of soil or a soil’s capacity to support a number of its functions (loss of soil quality). Soil degradation with respect to agriculture is mostly defined by eight threats, which contribute to the loss of the quality of the soil: loss of organic matter, erosion, floods, salinisation, compaction, landslides, contamination and sealing. These degradation processes are strongly correlated (Blum, 1998).

Soil degradation due to one or multiple disturbances of a soil can lead to a loss of some important soil's functions. The loss of soil functions can have great consequences with respect to nature, economy and human wellbeing as a whole (MIRA, 2011). Degradation of soil has a direct impact on the quality of water and soil, influences the food chains and climate change and hinders biosphere functioning (Tóth *et al.*, 2007).

2.7.1. Loss of organic matter

The most important feature of organic matter for a soil is its ability to form the binding and buffer capacity of the soil and to deliver energy to sustain life in the soil. It is the key to soil fertility and helps to limit diffuse soil contamination and buffering of the soil water environment. Organic matter gives strength to the soil by influencing its structure and is an important factor for physical soil quality (MIRA, 2011).

About 50% of the Soil Organic Matter (SOM) consists of Soil Organic Carbon (SOC). SOC is indispensable for ecosystem functioning. It has a major influence on the biological, physical (soil structure, water holding capacity) and chemical (cation exchange capacity, CEC, representing the ability to form complexes with metal ions and nutrients for storage) fertility of the soil (Milne *et al.*, 2007). Due to its high carbon content, SOM - and the soil in general - is an important factor for the global carbon cycle (MIRA, 2011).

The main reason for the decline of SOM is climate change, decoupling of cattle breeding and agricultural activities. Another important factor for SOM decline is the intensification of agricultural practices, e.g. higher frequencies and depth of tillage, continuous cropping and narrow crop rotations (Gardi *et al.*, 2008). The factors that need to be controlled in order to reduce the loss of SOM with respect to agricultural practices are crop rotation, tillage and management practice (Rickman *et al.*, 2002).

There are different ways to restore the SOM content in crop cultivation. Land management options such as reduced or no tillage, improved residue management, organic adjustment, and improved crop rotation are strongly recommended if necessary (Dawson and Smith, 2007).

2.7.2. Erosion

Soil erosion is defined as the process in which soil particles are detached, transported and deposited from a soil to another. The traditionally acknowledged types of erosion are water erosion (Schiettecatte *et al.*, 2008), wind erosion (Van Kerckhoven *et al.*, 2009) and mass transport (Van den Eeckhaut *et al.*, 2007). For agricultural soils, research (Govers *et al.*, 1994, Van Muysen *et al.*, 2000) has indicated that an important soil movement occurs due to management (sloping soils) and export of soil material due to harvest (Poesen *et al.*, 2001). Soil erosion results in the loss of soil and consequently the loss of soil functions (MIRA, 2011).

2.7.3. Floods

Flooding is strongly correlated with compaction and erosion of the soil (Gay *et al.*, 2009). For agricultural land use, flooding is not always considered to be a negative process. It has an important influence on the grade of soil salinisation (Tóth *et al.*, 2008) and is an important process influencing water status and anaerobic conditions necessary for rice cultivation.

The Mekong Delta is subjected to flooding during half of the year (1.2-1.8 million ha). This has negative effects with respect to human infrastructure but is positive in a way that salty and acid water is washed away and deposits of sediments provides fertilization for the soil (Hoa *et al.*, 2008).

2.7.4. Salinisation

Salinisation can be described as the process leading to an excessive amount of water-soluble salts in the soil (Várallyay and Tóth, 2006). Salinisation of the soil can be the effect of natural processes or can be caused by human activities, such as irrigation without sufficient drainage. Excessive salt content in agricultural soils causes decreasing of yield or even crop failure (Qadir *et al.*, 2008). Sodification occurs when the amount of sodium ions in the soil is too high and results in a deterioration of the soil structure.

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

2.7.5. Compaction

Soil compaction is the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density' (Soil Science Society of America, 1996). This is illustrated in Figure 2.2.

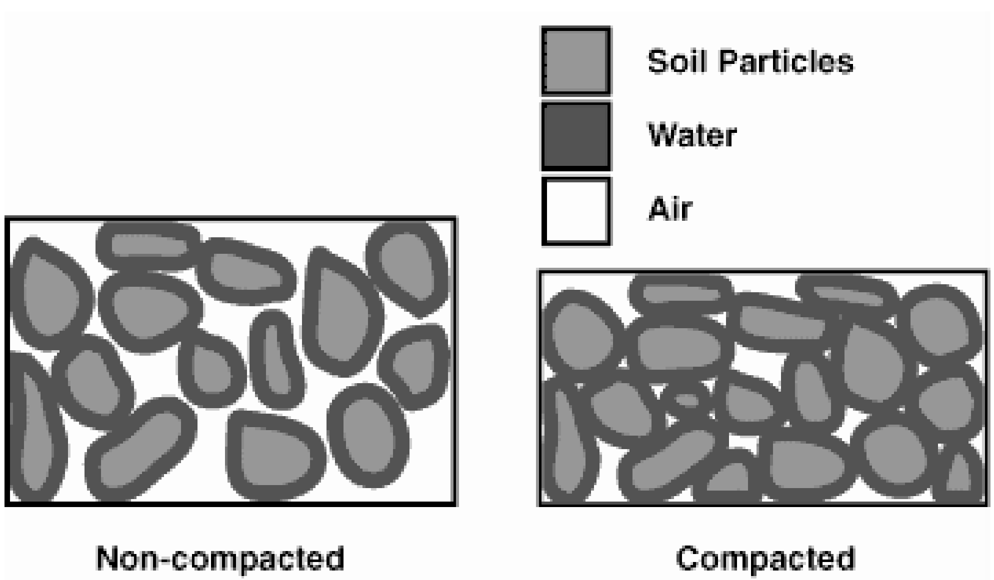

Figure 2.2: Effect of soil compaction on pore space in a soil

Soil compaction is one of the major problems in modern agriculture. Soil compaction occurs in a wide range of soils and climates. It increases soil strength and decreases soil physical fertility by decreasing storage and supply of water and nutrients. This also leads to additional fertilizer requirement, increasing the production cost. Compaction strengthens erosion effects and has a negative effect on crop root depth, water availability and aeration of the soil, resulting in a higher risk for crop failure and a reduction of plant growth (FAO, 2003). This leads to lower inputs of fresh organic matter to the soil, reduced nutrient recycling and mineralization, reduced activities of micro-organisms, and increased wear and tear on cultivation machinery (Hamza and Anderson, 2005). Compaction also affects the mineralization of soil organic carbon and nitrogen (De Neve and Hofman, 2000) as well as the concentration of carbon dioxide in the soil (Conlin and Driessche, 2000).

Compaction is strongly related to soil structure. Soil structure is defined by the arrangement and coherence of the solid soil particles. Coherent soil particles bond with SOM, forming stable structures or aggregates. The aggregates are separated by pore spaces, which can contain water and air. The smaller pores or micropores can hold water strongly whereas the larger pores or macropores are more often air-filled. Soil structure is of major importance for soil-water-air status and crop growth (Vandergeten and Roisin, 2004; Shepherd *et al.*, 2008). Compaction alters the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units (Defossez and Richard, 2002).

Soil compaction is mainly a human induced process (FAO, 2003). It is caused by pressure on the soil, mainly by agricultural practices (Le Bas *et al.*, 2006). The most important reasons for soil compaction are frequent use of heavy machinery, intensive soil operation, intensive cropping, short crop rotations and one-sided crop rotation. This effect is amplified by low SOM content and use of tillage and grazing at high soil moisture content (Jones *et al.*, 2004; Vandergeten and Roisin, 2004; Hamza and Anderson, 2005; Koopmans *et al.*, 2006; Ruebens *et al.*, 2010).

At compaction, a soil is compressed and deformed, leading to a decrease in total and air-filled pore space. Initially the larger macropores are compressed and by further compaction followed by the smaller micropores. This results in a decrease of the total macropore volume and interruption of the continuity of the canals. The sensitivity of a soil to compaction depends on its texture, apparent density and environmental conditions (Poesen *et al.*, 1996; Esteve *et al.*, 2004; Jones *et al.*, 2004; Ruebens *et al.*, 2010). The severity of compaction depends on the water content and the bearing capacity of the soil and the magnitude of the pressure force applied (Batey, 2009). Indication of soil compaction can be found when looking at orientation, size and shape of soil aggregates, increase in bulk density and reduction of porosity (Gardi *et al.*, 2008). Clay soils are the most susceptible soils for compaction (Gay *et al.*, 2009).

Intensive farming of crops and animals has spread all over the world and involves shorter crop rotations and heavier machinery, leading to an increase in soil compaction (Poesse, 1992).

Since the state of compactness is an important attribute for soil structure, there is a need to find a parameter for its characterization. An important parameter to characterize compaction is relative bulk density. Relative bulk density gives directly comparable values for all soils (Håkansson and Lipiec, 2000). Soil bulk density is the mass of dry soil per unit volume, indicating the relationship between soil compaction and its capacity to store and transport water or air. For this reason the dry soil bulk density is the most frequently used parameter for the characterization of the state of soil compactness (Panayiotopoulos *et al.*, 1994). Soil water infiltration rate can also be used to monitor the state of soil compaction, especially for the topsoil. Water infiltration is a lot easier and thus faster for uncompacted soils with well-aggregated soil particles than for massive, structureless soils (Hamza and Anderson, 2002, 2003).

An important side note on this matter is the fact that for some soil types and crops, a slight degree of topsoil compaction may be beneficial for crop growth (Bouwman and Arts, 2000) indicating that there is an optimum level of compaction for crop growth. This is an important feature in rice cultivation.

2.7.6. Contamination

Soil contamination is defined as the presence of certain products in the soil in such concentrations that it leads to a loss of soil functions. The most common contaminations are due to high levels of heavy metals and nitrogen/phosphorus. In agricultural soils nitrogen/phosphorus contamination is mostly the effect of fertilization processes (Gay *et al.*, 2009). These contaminations reduce the availability of nutrients to crops and the buffering and filtering capacity of the soil. This leads to yield reduction, leaching of nutrients to groundwater and eutrophication (Maréchal *et al.*, 2008).

In the Mekong Delta the use of inorganic fertilizers is very common and stimulated by the government with price incentives. The wrong use of fertilizers brings a risk to the health of farmer and consumer (Dung *et al.*, 2000). The low cost and ease of applying inorganic fertilizer hinders the introduction of organic fertilizers.

2.8. Temporal variability

Soil hydraulic properties have an impact on the hydrologic cycle and are thus important factors considering physical soil quality (Hu *et al.*, 2009). It has long been stated that these soil hydraulic properties vary spatially (Nielsen *et al.*, 1973; Sisson and Wierenga, 1981; Byers and Stephens, 1983; Hopmans *et al.*, 1988; Strock *et al.*, 2001). Many water and solute transport models take this spatial variability into account but assume that soil surface characteristics are constant in time. In reality, however, surface characteristics undergo temporal changes and thus show variability on the temporal scale as well. These temporal changes can be induced by, for instance, irrigation and tillage, rain and wind weathering, and biological activity, which can drastically modify soil structure (Imeson and Kwaad, 1990; Angulo-Jaramillo *et al.*, 2000).

In contrast with spatial variability, only little studies have been performed for the effect of temporal variability. The main reason for this is because measurements with respect to temporal variability are costly and time-consuming (Angulo-Jaramillo *et al.*, 1997). However, lately, temporal changes of soil physical properties have been the subject of much research in order to quantify the effect of different management systems within a growing season and between years. Because many soil properties are strongly dependent on the dynamics of soil structure, management systems are the primary agents for changing soil environmental conditions (van Es *et al.*, 1999; Alletto and Coquet, 2009). Properties such as particle density and particle size distribution usually show a small variation with time because they are more dependent on natural factors such as soil formation processes and parent material (Cassel, 1983). On the other hand, variables that are dependent on seasonal climatic conditions, management practices, crop development and biological activity show more variability with time. Soil parameters such as bulk density, saturated hydraulic conductivity and macroporosity are responsive to changes in land management. Parameters for matrix porosity do not respond substantially or consistently to changes in cropping and/or tillage practice (Reynolds *et al.*, 2007).

In agriculturally managed soil, the extent of temporal variability might even exceed spatial variability of soil physical properties. Studies with respect to the relative significance of sources of spatial and temporal variability at multiple scales on water infiltration capacity for agricultural lands, as performed by van Es *et al.* (1999) concluded that soil management factors are more important sources of variability than soil type. Soil physical and hydraulic properties are expected to vary significantly even in a short time period, such as during a crop cycle. This variability is especially significant immediately after tillage. Logsdon *et al.* (1993) notes that within-season changes in infiltration rates can be greater than management-induced differences.

Soil hydraulic conductivity, for example, is particularly sensitive to temporal changes. Experiments showed values of soil hydraulic conductivity near water-saturation immediately after ploughing that were about 100 times larger than values measured several months later. This reduction is the result of soil consolidation processes (Mapa *et al.*, 1986). However, Zhang *et al.* (2006) and Bormann and Klaassen (2008) found no significant seasonal variation for the soil hydraulic properties taken into account. In addition, although significant temporal changes of hydraulic conductivities were found in many places, the obtained results were often conflicting with each other. With time, decrease (Mapa *et al.*, 1986;

Alakukku, 1996), increase (Khakural *et al.*, 1992; Ciollaro and Lamaddalena, 1998), no systematic change (Starr, 1990; Logsdon and Jaynes, 1996) or no changes at all (Zhang *et al.*, 2006; Bormann and Klaassen, 2008) were observed for *K*. This conflict of results indicates the importance of site-specific research in the temporal variability of *K* and other factors, especially under natural conditions and different land uses.

Several researchers show that the hydraulic properties of soils can vary significantly in the long-term, but also in the short term through the growing season. In a particular soil-water-plant system, under particular climate conditions, the transport properties of the soil surface layer can undergo changes during the growing season. This temporal variability is possibly due to modifications in the conditions of the surface soil. Long-term changes in the hydraulic properties of soils, in relation to tillage history, have been well described, as well as short-term changes, within one season and with respect to changes as a result of processes such as surface crust formation, settlement of tilled soil under rainfall and root growth. However, the connection between long-term tillage history and short-term variability of soil hydraulic properties has rarely been studied. Neither has there been research on whether short-term variability in soil hydraulic properties can be used as indicators of soil structure decline. This appears to be very important since short-term changes in soil hydraulic properties may have a substantial influence on the interpretation and applicability of the measurements (Murphy *et al.*, 1993).

When evaluating the effects of different management systems on a soil, it is thus very important to assess the temporal changes of the soil physical properties within a growing period and within a year. The fact that soil hydraulic parameters are time-variant should therefore not be neglected in soil water flow modeling.

2.9. Modeling and Models

A model is generally defined as a simplification or abstraction of a real system (Loomis *et al.*, 1979). This is particularly the case for models describing a biological system, such as crops, where the real system is an interaction of a vast number of components and processes at different organisational levels (Sinclair and Seligman, 1996). A crop model can be defined as a quantitative scheme, useful for prediction of the growth, development and yield of a crop, given a set of genetic features and relevant environmental variables (Monteith, 1996).

Crop models can be useful for multiple objectives. Primarily, crop models interpret experimental results and serve as agronomic research tools for the synthesis of research-based knowledge. If a model is proven to be well functional it can be used to try out new ideas and strategies under different weather and climatic conditions before testing them in expensive and time-consuming field experiments (Ahuja *et al.*, 2006). This way lengthy and expensive field experiments can be preevaluated in order to sharpen the field tests and lower their overall cost (Whisler *et al.*, 1986). Field-tested crop models can be useful as decision support tools for system management, including site-specific management or precision agriculture (Ahuja and Ma, 2002) and for the assessment of optimum management practices, such as planting date, cultivar selection, fertilization, or water and pesticide usage. This information can be useful for seasonal and within-season decision-making. Furthermore, models can be of assistance in policy making, by predicting soil erosion, leaching of agrichemicals, effects of climatic change, and large-area yield forecasts (Boote *et al.*, 1996).

Depending on the purpose and objectives of the crop model, a distinction is made between two main modeling approaches: a scientific approach and an engineering approach. The scientific approach aims mainly at improving our understanding of crop behaviour, its physiology, and its responses to environmental changes. The second approach, the engineering approach, attempts to provide sound management advice to farmers or predictions to policymakers (Passioura, 1996). Scientific modeling is based on laws and theories of how the system functions, giving it a more mechanistic meaning. Engineering modeling on the other hand is based on a mixture of well-established theory and robust empirical relationships meant to be functional (Addiscott and Wagenet, 1985).

Another distinction can be made between complex and simple models. The difference between these two types is straightforward. There is a need for both types and the choice of the type depends on the objective of the model and practical possibilities. In some cases, the use of a simple model is not appropriate because the model is not programmed to address a particular phenomenon. In other cases, complex models are not preferred because they may require input parameters that are not practical to obtain in a field situation and are thus not available (Boote *et al.*, 1996).

It is important for modelers to be forthright in model description and promotion. Some questions should be asked and answered by the modeller. For example, what does a given model respond to and what factors does the model not address? What are the limitations of the model and inputs to run the model? Caution and knowledge of the model's limitations is important. Appropriate use of a model for a particular purpose depends on whether the model complexity is appropriate to answer the questions being asked and whether the model has been tested in diverse environments (Boote et al., 1996).

Due to the time-consuming character of in situ hydraulic conductivity measurements, only little work has been published with respect to small-scale temporal variability in hydraulic conductivity. Consequently this type of variability is generally not incorporated into simulation models (Alletto *et al.*, 2010). In Mubarak *et al.* (2009), results of research where this temporal variability effect was effectively incorporated in a simple model are reported. The research identified the temporal variability of the hydraulic properties of field soil under high-frequency water application with drip irrigation during a maize growing season. Results showed major differences between the computed results when model input parameters measured before and after irrigation were used. Knowledge about this change can improve the efficiency of both irrigation and fertilization of the root zone and reduce losses of both water and solute due to deep percolation. Mubarak *et al.* (2009) suggest that the temporal changes in soil hydraulic properties identified in the study should be taken into account in future studies when simulating soil water transfer under drip irrigation in order to improve irrigation scheduling practices. This conclusion suggests the need for further studies improving models accounting for temporal changes in soil hydraulic properties.

2.10. Aquacrop

The FAO model AquaCrop is a crop water productivity model that allows a simulation of attainable yield of the major herbaceous field and vegetable crops as a function of water consumption under rainfed, supplemental, deficit, and full irrigation conditions. The growth engine of AquaCrop is water-driven, making it especially suited to simulate conditions where water is a key limiting factor for crop production. AquaCrop requires only a limited number of explicit input parameters, which are mostly intuitive and easy to obtain. This way AquaCrop tries to balance simplicity, accuracy and robustness (Steduto *et al.*, 2009).

Aquacrop is a model of the engineering type on canopy level, mainly focusing on simulating the attainable crop biomass and harvestable yield in response to the available water. The model focuses on water because it is a key driver of agricultural production. On top of that, the constant growth of human population and the increased industrialization and living standards worldwide are demanding a greater share of our finite water resources, making water an increasingly important critical factor in the limitation of crop production. The crop response to water deficit is one of the most difficult responses to include in modeling, as water deficit is variable in intensity, duration and time of occurrence (Hsiao, 1973; Hsiao *et al.*, 1976; Bradford and Hsiao, 1982).

The aim of FAO with the AquaCrop model is to have a functional canopy-level water-driven crop simulation model of yield response to water that can be used for the wide range of agricultural systems that exist worldwide. The model is functional for a number of crops. However, model calibration and validation, specific for each crop, is performed as extensively as possible in order to improve and increase the applicability of the model for the main crops (Steduto *et al.*, 2009).

2.11. Crop requirements

A fertile soil is a soil that provides sufficient water, nutrients, oxygen, an adequate rooting depth, a good temperature and no toxicities for the cultivated crops. The exact properties that a soil needs to support are dependent on the requirements of the cultivated crops. Farmers manipulate these soil properties in order to reach the crop requirements and to attain higher yields (Wild, 2003). Sys *et al.* (1993) has provided the requirements for rice, maize and mungbean described in the next section.

2.11.1. Rice (*Oryza sativa*)

Rice is generally considered as a tropical crop. It is the most productive cereal growing in Asia on land at any altitude from below sea level up to 2700 m elevation. The average temperature for rice cultivation has to exceed 20°C and the minimum temperature cannot drop lower than 10°C for 4-6 months. The optimum temperature for rice growth is 30-32°C. Rice has a very high water demand and thus requires generous rainfall or irrigation. High relative humidity (RH) is favourable for crop growth through the vegetative stage but also favours diseases. High RH is common in Tropical Asia, especially during the rainy season. A low RH causes shrunken grains. Light is not a limiting factor in early stages of rice growth but becomes more critical with the age of the plant. The requirements of the slope and landform for the cultivation depend on the type of rice culture. Terracing is a possible method to allow rice cultivation on slopes.

2.11.2. Maize (*Zea mays*)

Maize is a crop that is widely cultivated and consumed. It 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 generally grows in a temperature range of 14-40°C although the optimum range is 18-32°C. For optimum water supply, the total amount of rainfall for one growing season should be 500-1200 mm. Non excessive RH is favourable. Many types of soil can be used for maize growth. Most suitable are well drained an aerated, deep loam and silt loam soils with adequate organic matter.

2.11.3. Mungbean (*Vigna radiata*)

Mungbean is originally from India and is a much-preferred bean because it is a rather light bean species. Mungbean is generally not grown in the lowland humid tropics. Soil temperature for germination should exceed 15°C. The optimum temperature for crop growth ranges from 15-20°C. Mungbean is sensitive to frost and to temperatures higher than 30°C. The total precipitation during the growing season should be 400-500 mm. Excessive rain causes flower drop and diseases. Medium to high relative humidity is required, especially at flowering. The crop is sensitive to water logging, so the soils should be well drained. Ideal texture for crop cultivation is loam tot clay loam.

3. MATERIAL AND METHODS

3.1. Study area

The study was performed at a field located in Long Khanh village (latitude 10°22’51’’ N and longitude 106° 7’03’’ E), Cai Lay district, Tien Giang province in the Mekong Delta, Vietnam (Figure 3.1).

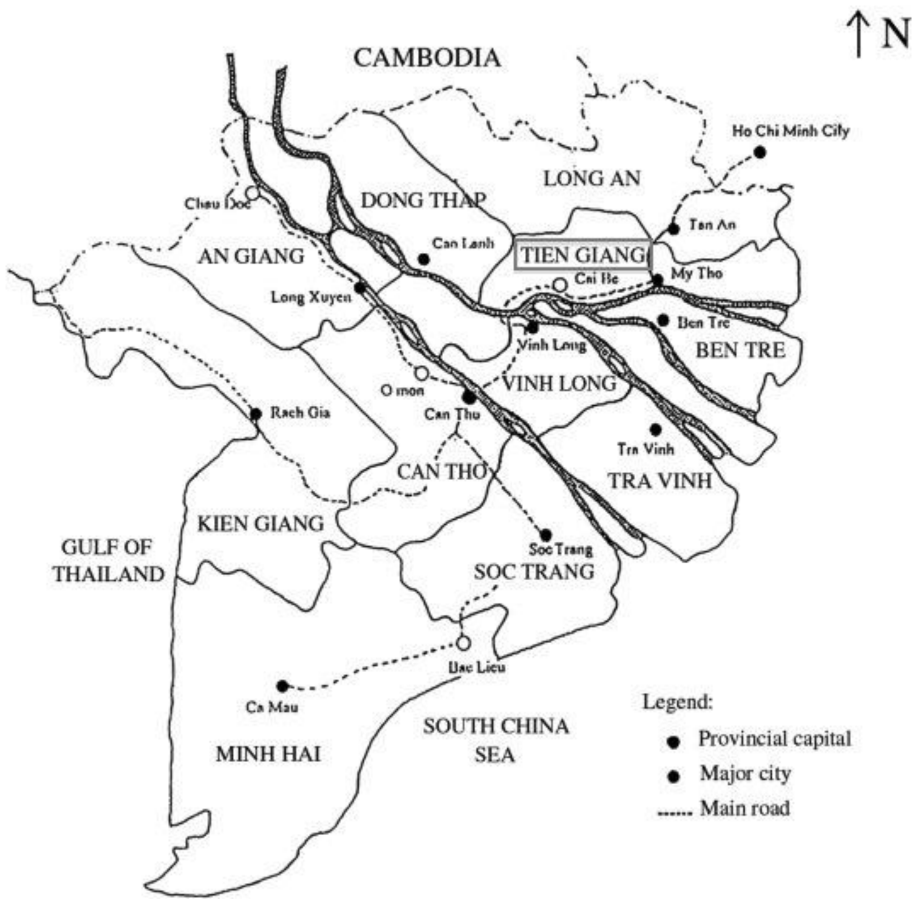

Figure 3.1: Map of the Mekong Delta, with the province of the study location indicated in the square.

The field is located 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 mm and 1,400 mm. The temperatures are stable throughout the year and have an average value varying from 25°C to 28°C. Average radiation is 162 $Kcal.cm^{-2}.year^{-1}$ and there are about 2,709 hours of $sunshine.year^{-1}$. Most of these climatic factors are favourable 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 to 50 cm (Tran Ba, 2004).

Figure 3.2 shows the average temperature and total precipitation for each month during the year of measurement (2011-2012), which were recorded at the weather station (Cai Lay, Tien Giang province) representative for the climatic conditions at the experiment field. It can be seen that the present climate at the experimental field is optimal for rice cultivation, especially during the wet season (June – November). Temperatures are within the range of 20°C and 35°C for the entire year which is preferable for the cultivation of rice and maize and in a lesser way for mungbean. Mungbean needs only 400-500 mm during its crop cycle while maize has a higher precipitation demand. Therefore the rotation is preferably scheduled in a way that mungbean is cultivated in the summer-autumn cycle, from March to June. The best growing season for the cultivation of maize would then be the autumn-winter cycle, from June to October. If maize and rice are cultivated during a period of low precipitation additional irrigation can be used to meet their requirements.

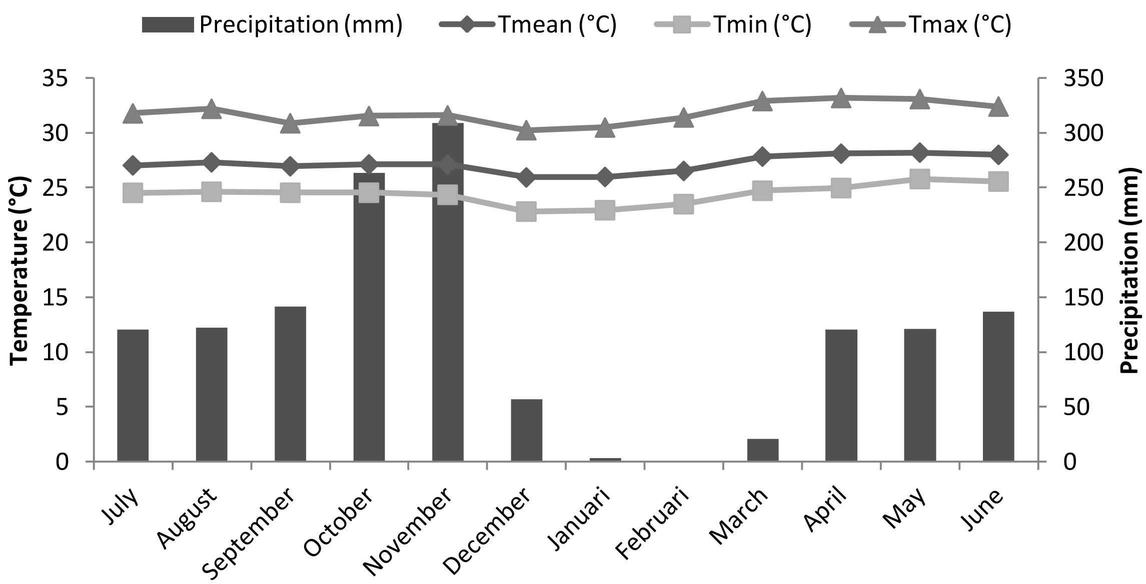

Figure 3.2: Rainfall distribution and average temperature at the experimental field for the year of experiment (July 2011 - June 2012).

The climatic data can be used for calculation of the reference evapotranspiration ET_0 (mm.day^{-1}) using the software EToCalculator (FAO, 2009) based on the FAO Penman Monteith equation (Eq. 1) (Allen *et al.*, 1998). Missing data were estimated according to Allen *et al.* (1998).

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \qquad \text{(Eq. 1)}$$

where ET_0 is reference evapotranspiration (mm.day^{-1}), Δ is slope of the vapor pressure curve (kPa.°C^{-1}), R_n is net radiation at crop surface (MJ.m^{-2}.day^{-1}), G is soil heat flux density (MJ.m^{-2}.day^{-1}), γ is psychometric constant (kPa.°C^{-1}), u_2 is wind speed at 2 m (m.s^{-1}), e_s is saturated vapor pressure (kPa), e_a is actual vapor pressure (kPa).

3.2. Experimental design

The experimental field is a complete block design that is randomly divided in 24 rectangular plots of equal size with an area of 42 m^2. Each of the six land uses and land management practises considered in the experiment were repeated four times on four different plots.

The six treatments considered are:

1. Rice monoculture: rice – rice – rice + inorganic fertilizer (IOF)
2. Rice monoculture with addition of organic manure: rice – rice – rice + organic fertilizer/manure (OM, 10 tons/crop season)
3. Crop rotation of rice and maize: rice – maize – rice + IOF
4. Crop rotation of rice and maize with addition of organic manure: rice – maize + 10 tons OM – rice
5. Crop rotation of rice and mungbean: rice – mungbean – rice + IOF
6. Crop rotation of rice, mungbean and maize: rice – mungbean – maize + IOF

All six treatments are crop rotation systems consisting of three crop cycles in a year. Each cycle has duration of three months (90 days). The first crop cycle is called the winter-spring cycle, which starts in November and ends in February. Secondly there is the summer-autumn cycle from March to July and thirdly the autumn-winter cycle from July to October. In the rotation systems where one upland crop is introduced, cultivation of the upland crop is performed during the winter-spring cycle in the dry season. This experimental design has been used on the test field for 12 years before measurements were taken in 2011-2012. It is believed that after these 12 years the impacts of the treatments should be sufficient to distinguish the possible differences in soil physical properties that are examined, and their variability during the crop growing cycle.

Sampling and measurements were performed for the winter-spring and summer-autumn cycles, three times per cycle, i.e. 15 days after sowing (DAS), 45 DAS and 90 DAS (at harvest). Two undisturbed soil samples (see 3.3.2) per plot, i.e. eight per treatment, were taken each time at three depths, i.e., 0-10 cm, 10-20 cm and 20-30 cm, using steel-metal cylindrical Kopecky rings with a volume of 98.125 cm^3. The sampling location within the plot is chosen randomly.

Rice cultivation was performed on puddled soils while for the upland crops (maize and mungbean), bed rows with a height of 20 cm above the field surface were prepared, using the soil next to the bed rows. The latter provided soil turning between the Ap and AB-horizon. Rice cultivation requires a flat surface to maintain submerged conditions; therefore, the soil was tilled and levelled before sowing of the rice.

The soil profile description as provided by Tran Ba (2004) can be found in APPENDIX I. The description was made up to a depth of 130 cm. The topsoil shows an accumulation of brown alluvial material, mixed with common brown fresh roots. The soil is ripe and nearly ripe up to a depth of 130 cm and from the depth of 130 cm, the texture is sandy loam. It was classified as a Gleyic Fluvisol (Soil Science Department, Can Tho University, 2005; Soil Survey Staff, 1998). Classification was based on the USDA/Soil Taxonomy Classification system (1996).

3.3. Soil analysis

Following physical characteristics of the soil were considered in this study: bulk density, total porosity, macroporosity, matrixporosity, infiltration rate and hydraulic conductivity.

3.3.1. Field measurements

Infiltration rate and hydraulic conductivity values were determined with a single-ring infiltrometer on the field (Figure 3.3). The single-ring infiltrometer is used primarily for measuring cumulative infiltration, I (L), infiltration rate, i = di/dt ($L.T^{-1}$), and field-saturated hydraulic conductivity or 'infiltration capacity', K_{fs} ($L.T^{-1}$).

Although it is generally suggested that a buffer ring should be installed around the infiltrometer to make sure the water infiltrating from the infiltrometer will percolate vertically into the soil, thereby preserving the integrity of the measurement, like with the widely-used double-ring infiltrometer, we have opted for a single-ring infiltrometer. A large number of comparisons between buffered and non-buffered measurements, generally conclude that the spatial variability in the field is much larger compared to the effect of buffering making it unnecessary to install and operate the buffer of the additional ring. In addition, most comparisons cannot detect the effect of the buffer (Verbist *et al.*, 2010). Given the accuracy of the method in describing representative infiltration, it is believed that any error caused by leaving out the buffer is insignificant (FAO, 2013).

Complete instructions on the use of a cylinder infiltrometer are presented in Haise *et al.* (1956). The infiltrometer used had a metal cylinder with a diameter of 28 cm. This cylinder was driven firmly into the soil to a depth of about 15 cm, using a driving plate set on top of the infiltrometer and a heavy hammer. The cylinder was filled with water up to a certain height. At this point water input in the cylinder was stopped and the water level dropped as a result of infiltration in the soil. The height difference of the water level in the cylinder was measured as a function of time for a period of 90 minutes.

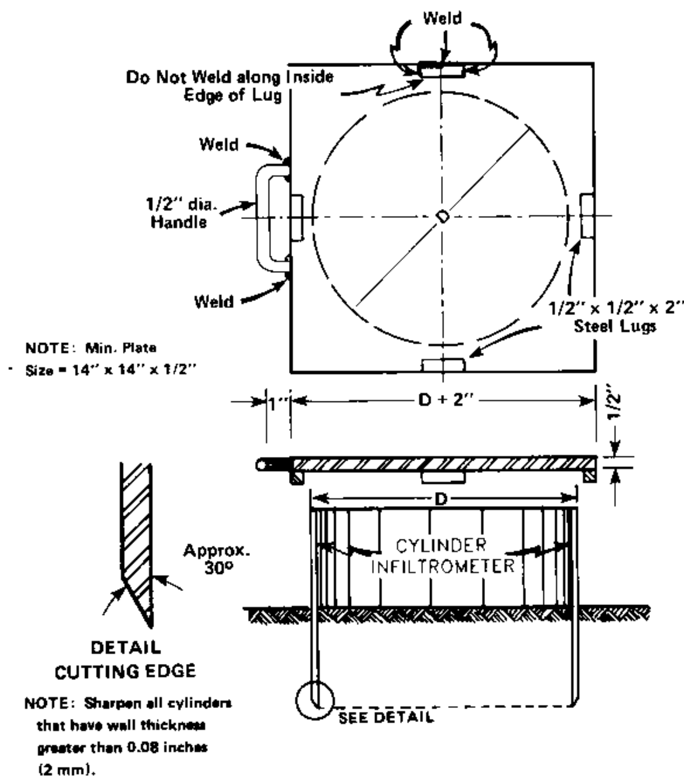

Figure 3.3: Schematic representation of a ring infiltrometer and driving plate (after Haise *et al.*, 1956)

3.3.1.1. Infiltration rate

Cumulative infiltration I is the total amount of water infiltrating in an area-unit of the soil from the beginning of water application until the moment of measurement. One of the most-widely used models to describe cumulative infiltration I (expressed in m) with time is the Philip equation (Philip, 1957). However, with this method unrealistic parameter values for infiltration rate and saturated hydraulic conductivity were obtained. Therefore, infiltration rate was calculated with the equation of Kostiakov (1932):

$$I = a \cdot t^{b} \qquad \text{(Eq. 2)}$$

where t is time of infiltration (s), and a and b are empirical constants, which are function of the soil's characteristics.

The infiltration rate i (expressed in $m.s^{-1}$) is the amount of water infiltrating in an area-unit of soil in a unit of time. In can be derived from eq. (1):

$$i = \frac{dI}{dt} = a \cdot b \cdot t^{b-1} \qquad \text{(Eq. 3)}$$

Both theory and experiment have shown that infiltration rate through a ring or cylinder infiltrometer is initially large but decreases with time to approach a quasi-steady-state value, which is related to the infiltration capacity of a soil. The time required to reach this quasi-steady-state is dependent on the diameter of the ring or cylinder. The bigger the diameter, the longer it takes to reach quasi-steady-state

(Youngs, 1987, 1991). The term 'quasi' is used because the approach of a real steady-state for ring infiltrometers can be very slow or even asymptotic.

For the experiment, infiltration rate was calculated with a time value equal to 5 hours after the beginning of the experiment.

3.3.1.2. Field-saturated hydraulic conductivity

Values for hydraulic conductivity were calculated from the infiltration data. When the saturated hydraulic conductivity is measured via infiltration into initially unsaturated soils, which is the case for this experiment, it is often referred to as field-saturated hydraulic conductivity or "infiltration capacity", K_{fs} (Reynolds *et al.*, 1983). The reason for this is the fact that air is usually entrapped in a porous medium when the medium is saturated by infiltration of water, especially during downward infiltration under ponded conditions, such as when ring infiltrometer measurements are conducted. Due to this air-entrapment the water content of a porous medium at field-saturation will be generally lower than at complete or true saturation Ksat (Hillel, 1980).

Field saturated hydraulic conductivity was derived with the equation of Reynolds and Elrick (1990):

$$\frac{q_s}{K_{fs}} = \frac{Q}{\pi a^2 K_{fs}} = \frac{H}{C_1 d + C_2 a} + \frac{1}{\alpha^*(C_1 d + C_2 a)} + 1 \qquad \text{(Eq. 4)}$$

where q_s ($L.T^{-1}$) is quasi-steady infiltration rate (corresponding to i at 5 hours as described in 3.3.1.1.), Q (L^3T^{-1}) is the corresponding quasi-steady flow rate, a (L) is the radius, H (L) is the steady depth of ponded water in the ring, d (L) is depth of ring insertion into the soil, $C_1 = 0.319\pi$ and $C_2 = 0.184\pi$ are dimensionless quasi-empirical constants that apply for $d \geq 3$ cm and $H \geq 5$ cm (Reynolds and Elrick, 1990; Young *et al.*, 1995). α^* is the soil macroscopic capillary length parameter and represents the relative importance of the gravity and capillarity forces during infiltration (Raats, 1976). Values of α^* can be estimated from soil texture and structure categories. Based on Table 3.1, a value of $\alpha^* = 0.01$ cm^{-1} was chosen.

Table 3.1: Soil texture-structure categories for site-estimation of α^* (adapted from Elrick *et al.*, 1989).

Soil Texture/Structure category	*α^* (cm^{-1})*
compacted, structureless, clayey materials such as landfill caps and liners, lacustrine or marine sediments, etc.	0.01
soils that are both fine textured (clays) and unstructured.	0.04
most structured soils from clays through loams; including unstructured medium to fine sands. (the first choice for most soils)	0.12
coarse and gravelly sands; may include some highly structured soils with large cracks (vertisols) and macropores	0.36

The equation identifies three main components of quasi-steady-state flow from ring infiltrometers. The first term on the right of the equation represents flow due to the hydrostatic pressure of ponded water in the cylinder. In the second term the flow due to the capillarity (capillary suction) of the unsaturated soil under and adjacent to the cylinder is represented. Lastly, the third term represents flow due to gravity.

This equation can now be used to directly determine the value of the field-saturated hydraulic conductivity K_{fs}:

$$K_{fs} = \frac{q_s}{\frac{H}{C_1 d + C_2 a} + \frac{1}{\alpha^*(C_1 d + C_2 a)} + 1} \qquad \text{(Eq. 5)}$$

3.3.2. Lab analysis

3.3.2.1. Bulk density

Soil dry bulk density (BD) is often used in soil quality studies to qualify the soil's strength and give an index of the mechanical resistance of the soil for root growth (e.g. Carter, 1998, 1990; Reynolds *et al.*, 2003; Drewry, 2006). Soil dry bulk density is defined as:

$$BD = \frac{M_S}{V_b} \qquad \text{(Eq. 6)}$$

where M_S is mass of oven-dry soil (105°C) in Mg (ton), and V_b is bulk volume of the soil in m^3.

3.3.2.2. Macroporosity and matrix porosity

The macroporosity (MacPOR) and matrix porosity (MatPOR) parameters define the volume of soil macropores and matrix pores. They are determined as suggested by Reynolds *et al.* (2007):

$$MacPOR = \theta_s - MatPOR \qquad \text{(Eq. 7)}$$

$$MatPOR = \theta_m \qquad \text{(Eq. 8)}$$

where θ_s is the saturated volumetric water content of the soil ($m^3.m^{-3}$), and θ_m the saturated volumetric water content of the soil matrix exclusive of macropores ($m^3.m^{-3}$).

Matric head values of -0.1, -0.5 and -1 m were used to determine θ_m, which corresponds with drainage of pores with respective diameters of 0.3, 0.06 and 0.03 mm respectively, according to the capillary rise equation of Hillel (1980).

The method used for determinating θ_m was the sandbox method presented by Eijkelkamp Agrisearch Equipment (Giesbeek, the Netherlands). The undisturbed soil samples were saturated and placed in the sandbox chamber. An underpressure was forced upon the samples corresponding to matric head values of -0.1, -0.5 and -1 m. For each moisture tension, the samples were weighted, and water content was determined gravimetrically:

$$w = \frac{W_{water}}{W_{dry\ soil}} = \frac{W_{dry\ soil\ +\ water\ +\ ring} - W_{dry\ soil\ +\ ring}}{W_{dry\ soil\ +\ ring} - W_{ring}} \qquad \text{(Eq. 9)}$$

where w is gravimetric water content, W_{water} is weight of water in the soil sample (g) and $W_{dry\ soil}$ weight of a completely dry soil sample (g).

Volumetric water content θ was then obtained as:

$$\theta = w \cdot \frac{\rho_b}{\rho_w} \qquad \text{(Eq. 10)}$$

with ρ_w the density of water (g cm^{-3}).

3.4. Statistical analysis

Statistical analysis of the effect of different treatments on physical soil properties and the temporal variance of these properties for each treatment was performed using the one way analysis of variance (ANOVA) for the randomized complete block design. Significant temporal differences and differences between the treatments were determined using Duncan's multiple range test (DMRT) at 0.05% significance level.

Multiple factor ANOVA was performed on the data to reveal the effects of the season, time, treatment and depth, and two-way interactions between these factors. The threshold of significance for the statistical tests was chosen at 0.01%. Analysis was performed using SPSS Statistics 21.

3.5. Simulation with AquaCrop

The mechanism on which AquaCrop is based, is presented in the flowchart in Figure 3.4. The underlying idea of AquaCrop is simulation of the soil water balance from simple input data. This soil water balance and known crop parameters determine canopy and crop development and by means of the water productivity, the biomass and subsequently yield can be derived. A brief explanation of the working mechanisms of AquaCrop is discussed in this chapter. It is almost entirely based on Raes *et al.* (2012).

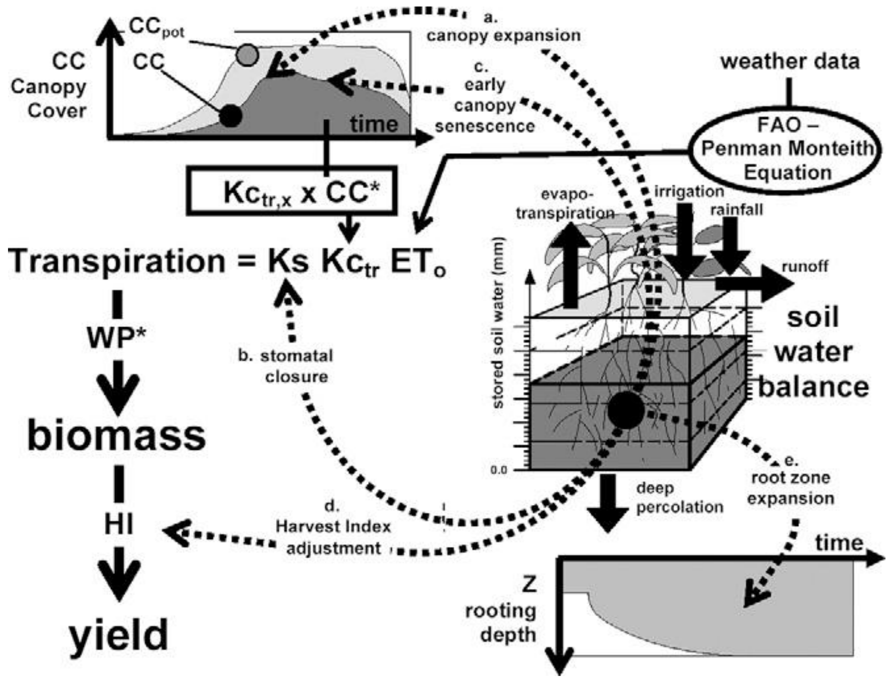

Figure 3.4: Graphical presentation of the flowchart of AquaCrop. The dotted arrows indicate the processes affected by water stress (Raes *et al.*, 2009)

3.5.1. Soil water balance

The root zone can be seen as a reservoir. The amount of water in this reservoir can be simulated by subtracting the outgoing water fluxes (evapotranspiration, surface runoff and deep percolation) from the incoming (rainfall, irrigation and capillary rise). The soil water stored in the root zone can be expressed as equivalent depth (W_r) or as root zone depletion (D_r):

$$W_r = 1000.\theta.Z \qquad \text{(Eq. 11)}$$

$$D_r = 1000.(\theta_{FC} - \theta).Z = W_{r,FC} - W_r \qquad \text{(Eq. 12)}$$

where W_r is the soil water content of the root zone (mm), $W_{r,FC}$ is soil water content of the root zone at field capacity (mm), D_r is root zone depletion (mm), θ is volumetric water content in the root zone ($m^3 \cdot m^{-3}$), θ_{FC} is volumetric water content in the root zone at field capacity ($m^3 \cdot m^{-3}$), and Z is the effective rooting depth (m)

The total available soil water (TAW) determines the maximum amount of water that a crop can potentially extract from the root zone. The water content above field capacity will be lost by drainage and the water content below permanent wilting point is too strongly retained by the soil matrix and thus not available for plants.

$$TAW = 1000.(\theta_{FC} - \theta_{PWP}).Z = W_{r,FC} - W_{r,PWP} \quad \text{(Eq. 13)}$$

where TAW is the total available water (mm), θ_{FC} is the volumetric water content in the root zone at field capacity ($m^3.m^{-3}$), θ_{PWP} is volumetric water content in the root zone at permanent wilting point ($m^3.m^{-3}$), Z is effective rooting depth (m), $W_{r,FC}$ is soil water content of the root zone at field capacity (mm), and $W_{r,\mathrm{PWP}}$ is the soil water content of the root zone at permanent wilting point.

3.5.2. Soil water stress

Crops experience water stress when the soil water content in the root zone drops below a certain threshold. This threshold is expressed as a depletion factor (p) of TAW. Soil water stress has a negative effect on canopy cover development and root expansion. Stress results in closure of the stomata, reduction of crop transpiration, pollination failure and early canopy senescence. Finally, the Harvest Index (HI) is altered.

In AquaCrop, the degree of water stress is expressed by a water stress coefficient Ks. Most processes define an upper and lower threshold. As long as the upper threshold for root zone depletion ($D_r < p_{upper}TAW$) is not exceeded, Ks is equal to 1 and no water stress is experienced by the plant. When the root zone depletion falls below the lower threshold ($D_r > p_{lower}TAW$), Ks is equal to 0 and plant stress maximal. When root zone depletion is somewhere in between these thresholds, the magnitude of the water stress is determined by the shape of the Ks curve, which can be linear, concave of convex.

3.5.3. Canopy development

In contrast with most models, which require input of Leaf Area Index (LAI), AquaCrop makes use of green canopy cover (CC) for describing the development and senescence of the crop. For optimal conditions, canopy development can be described by following parameters, as illustrated in Figure 3.5:

- CC_0 = initial canopy cover at 90% crop emergence (%)
- CGC = canopy growth coefficient ($\%.day^{-1}$)
- CC_x = maximum canopy cover (%)
- CDC = canopy decline coefficient ($\%.day^{-1}$)
- Start of senescence as days from sowing or planting

Following water stress coefficients for canopy development are considered in AquaCrop:

- $Ks_{exp,w}$ = water stress coefficient for leaf expansion growth
- Ks_{sen} = water stress coefficient for the early canopy decline

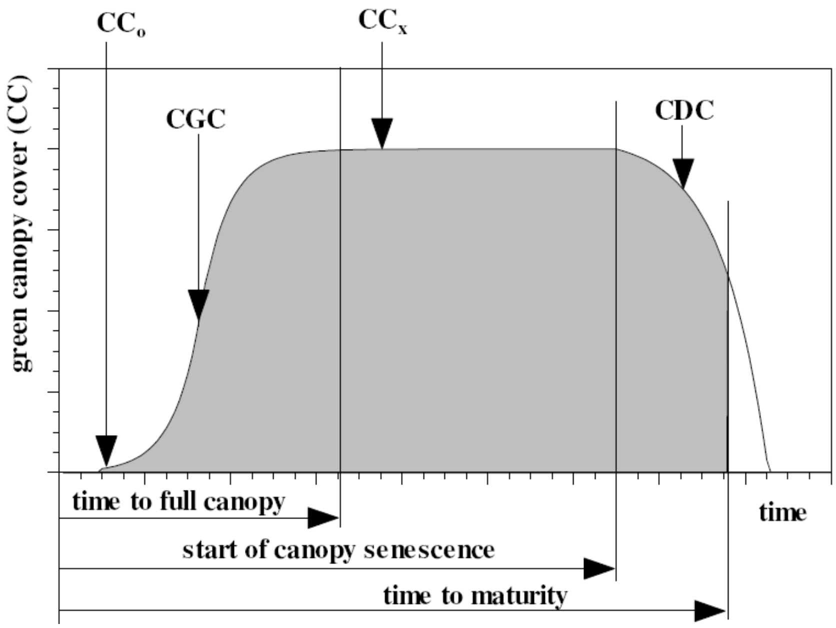

Figure 3.5: Green canopy cover (CC) throughout growing cycle under optimal conditions (Raes *et al.*, 2010).

3.5.4. Root zone expansion

Root depth development is function of crop type and of time. Maximum rooting depth is reached when crop development is optimal (no stress or restrictive rooting layer). When root zone depletion exceeds the upper threshold for stomatal closure (Dr > p_{sto}TAW), water stress affects the development of the roots. To account for this, AquaCrop considers a water stress coefficient for stomatal closure (Ks_{sto}). When water stress occurs, conditions for root growth become less than optimal and the water stress coefficient becomes smaller than 1.

3.5.5. Evapotranspiration

With the use of canopy cover, evapotranspiration can be calculated. Evapotranspiration is separated into crop transpiration (Tr) and soil evaporation (E). For a well-watered root zone and optimal management (no stress due to soil fertility, pests or diseases, salinity, etc.), soil evaporation and transpiration are maximal. The calculation method for ET is given in Eq. 14:

$$ET=(Kcb + Ke)\ ET_0 = Tr + E \qquad \text{(Eq. 14)}$$

where ET is evapotranspiration (mm.day^{-1}), ET_0 is reference evapotranspiration (mm.day^{-1}), Kcb is crop transpiration coefficient (-), and Ke is soil water evapotranspiration coefficient (-)

ET_0 equals evapotranspiration of a grass reference surface without water stress and under optimal management practices. The canopy cover determines the value of the coefficients Kcb and Ke. The crop transpiration coefficient is proportional to the green canopy cover (Kcb ~ (CC). The soil water evaporation coefficient is proportional to the fraction of bare soil, the fraction that is not covered by the crop canopy (Ke ~ (1-CC)).

When the crop is suffering from stress, optimal conditions and consequently potential transpiration is not reached. The actual transpiration is the transpiration of the crop under actual conditions and can be less than the potential transpiration due to stress.

3.5.6. Biomass production

The aboveground biomass is derived from the simulated amount of water transpired by the crop by means of the crop water productivity (WP). Crop water productivity equals the aboveground dry matter (g or kg) produced per unit of land (m^2 or ha) and per unit of transpired water (mm). In AquaCrop a normalized biomass water productivity (WP*) is used. This WP* is adjusted when running a simulation with an atmospheric CO_2 concentration different from the reference value (i.e. 369.41 ppm measured at Mauna Loa, Hawaii for the year 2000). A distinct is made between C3 and C4 crops with respect, which have differences in WP*.

Finally WP* can be adjusted for the type of synthesized products and soil fertility, leading to the adjusted normalized water productivity WP*adj. The daily aboveground biomass production is then calculated by Eq. 15:

$$B = WP^*_{adj}\left(\sum_i \frac{Tr_i}{ET_{0,i}}\right) \qquad \text{(Eq. 15)}$$

where B is total aboveground biomass production ($g.m^{-2}$ or $ton.ha^{-1}$), WP^*_{adj} is adjusted normalized crop water productivity ($g.m^{-2}$ or $ton.ha^{-1}$), Tr_i is daily crop transpiration on day i of the growing cycle ($mm.day^{-1}$) and $ET_{0,i}$ is daily reference evapotranspiration on day i of the growing cycle ($mm.day^{-1}$)

3.5.7. Yield formation

Finally, yield (Y) ($g.m^{-2}$ or $ton.ha^{-1}$) is simulated by means of a harvest index HI. The reference Harvest Index (HI_0) is a crop specific parameter is equal to yield mass per total aboveground biomass at maturity under optimal conditions. If stress occurs during the growing cycle, HI_0 is adjusted to HI. The adjustment is dependent on the development stage at the occurrence of stress and can have a negative or positive effect on the final value of HI. The final yield is calculated by:

$$Y = HI.B \qquad \text{(Eq. 16)}$$

3.5.8. Model calibration

AquaCrop was calibrated for rice grown in the winter-season of 2012 only due to absence of data for maize and mungbean in the spring-autumn season. This was done for the six treatments, allowing verification of the simulation effects for multiple treatments. A manual calibration was performed in a stepwise manner as recommended by Raes *et al.* (2012). By variation of parameter values according to the trial and error concept, the best possible representation of reality for the studied case was attained. First, crop parameters like maximum canopy, flowering, senescence and maturity (canopy development) were adjusted so that simulated canopy cover CC matched the observed value. Crop parameters like evapotranspiration and reaction to stress were considered as conservative, i.e. not locally dependent and were taken from the crop files provided by AquaCrop as recommended by Raes *et al.* (2012). Secondly, the soil physical properties porosity, water content at field capacity and wilting point, taken at matric potentials of -33 kPa and -1500 kPa, respectively, and field saturated hydraulic conductivity were considered, aiming at an optimal match between simulated and observed soil water content. The soil physical properties used in the calibration are were derived by Van Elsacker (2011) in 2010, at the end of the growing season and were not adjusted during calibration. The latter is the total amount of water over the rootzone hence expressed as equivalent depth (in mm). Finally, simulated biomass was compared with observed biomass and production parameters and canopy development (minor adjustments) was adjusted in order to have the best match. Since only data of one year were available, the model was not calibrated for yield and the HI value from the AquaCrop manual was used.

In each of these steps, the goodness-of-fit between observed and simulated data of canopy cover, biomass and soil moisture content was considered using the statistical comparison tool incorporated in AquaCrop. Five statistical parameters were thus included for this evaluation: the coefficient of determination (R^2), Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMSE), Nash-Sutcliffe model efficiency coefficient (EF) and Willmott's index of agreement (d).

3.5.9. Input data for AquaCrop

3.5.9.1. Climatic Input

The climatic data were collected from Cai Lay weather station (Tien Giang province) and are representative for the experimental plots. The total rainfall amount during the period considered in the simulations (July 1st, 2011 to June 30th, 2012) was 1415 mm. This is lower than the average rainfall amount of 1629 mm that was measured for this area in the period of 1979 to 2006. Frequency analysis using a Weibull distribution (Raes *et al*., 2006) showed that this annual rainfall amount has a return period of about 1.25 years and an 80% probability of exceedance. This means that our study period was rather dry. However, rainfall for this period was not very much lower than the average for this region and water from the Mekong river canals was also available for irrigation. Figure 3.6 shows the variation in daily rainfall over the study period, as well as calculated ET_o values (Eq. 1). Daily minimum and maximum temperature was rather constant within the year and varied from 19.7 to 27.1 °C and 26.8 to 35.2 °C, respectively. CO_2 concentration was 369.41 ppm, which is the default for Mauna Loa, Hawaii.

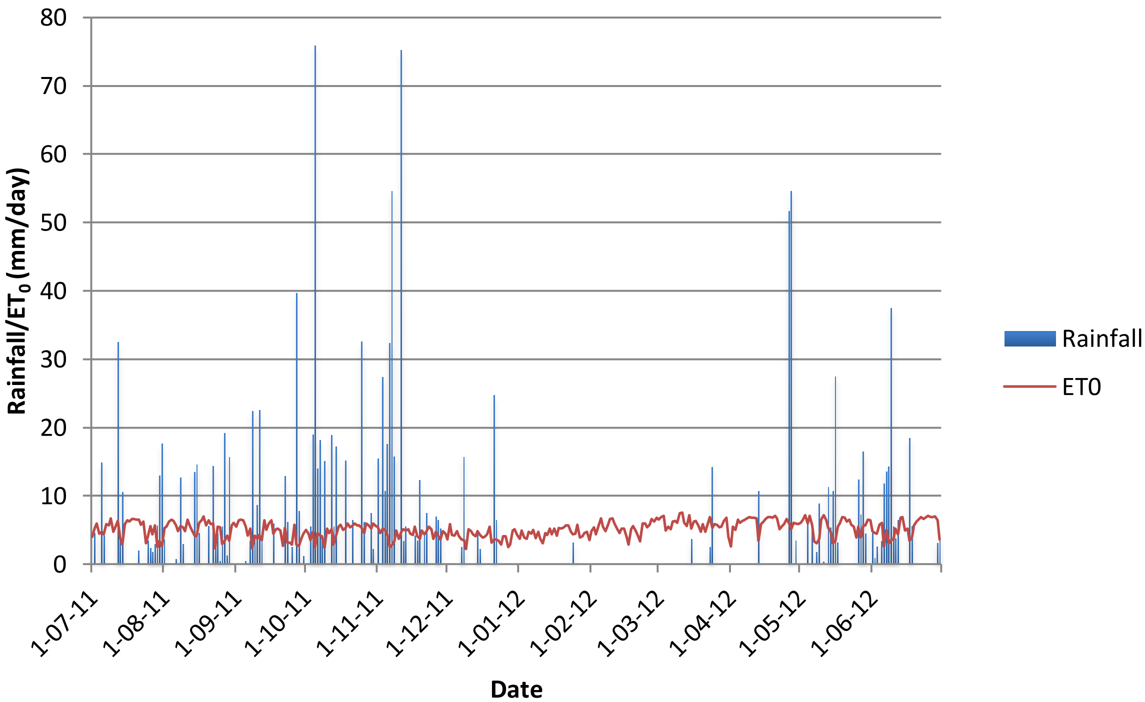

Figure 3.6: Variation in daily rainfall and calculated ET_0 for the study period from 1 July 2011 to 30 June 2012.

3.5.9.2. Crop input

AquaCrop presents a default crop file for paddy rice. This file was altered to approximate the crop conditions representative for our research. This file was calibrated manually until the goodness-of-fit (expressed by statistical parameters) for the predicted (simulated) and observed (measured) results was approaching an optimal value. Most adjustment were made in the crop development calendar, based on personal communication about the general occurrence of maximum canopy (±40 DAS), flowering stage (±50 DAS), start of senescence (±70-75 DAS) and maturity stage (±85 DAS) of the rice crop. Rice was harvested at 90 DAS.

Canopy cover needed for model calibration was estimated in a fairly simple way. Within an area of 0.25 m^2, the part of unshaded area on the ground was determined, with two replications per plot. The percentage of the canopy cover was estimated by visually comparing the unshaded areas with the shaded ones. Measurements were performed at midday.

Biomass samples (for model calibration as well) were taken through a squared frame of 0.25 m^2. Rice plants were cut and transported to the lab. Samples were dried in an oven at 105 °C for about 24 hours. After drying the samples were weighed and biomass was determined.

3.5.9.3. Field management and irrigation scheme

The water that is used for crop production was mostly derived from rainfall and flooding by irrigation. The presence of a plow layer prevented percolation of water from rainfall and flooding to the deeper soil layers, making it more available for the rice crops. The water for irrigation was obtained from the Mekong river canals and was stored in basins for later use. Water stress should therefore not be a significant problem for our test fields. The irrigation scheme that was used in AquaCrop is based on personal communication, although the correctness of this scheme might be doubtful. A more exact scheme could lead to better simulation results of soil water content.

The field plots were separated by soil bunds with a height of 40 cm. These soil bunds prevent surface runoff of irrigation water, making irrigation more efficient and improving infiltration of water in the soil due to longer flooding times.

3.5.9.4. Soil water content and soil profile description

A soil file representative for Cai Lay was created in AquaCrop based on textural data obtained from Can Tho University (CTU). The values for Ksat, soil water content at field capacity, permanent wilting point and saturation (set equal to porosity) required for the soil file were taken from this data, which can be found in APPENDIX II. Data was available up to a depth of 130 cm. For our study, however, the top 30 cm (up to the plow layer) was most important and measurements with respect to temporal variability were only taken (and relevant) for the upper 30 cm. A soil file based on the initial soil data as presented in APPENDIX II was used during calibration of crop parameters for the model. The initial soil water content at the beginning of the simulation was chosen as a default value at field capacity.

The soil water content was measured gravimetrically by taking soil samples with depth intervals of 10 cm, which were then transported to the lab. The samples were dried in an oven at 105°C for about 24 hours. The oven-dried samples were weighted and the soil water content was determined.

After calibration, this soil input file was altered and the effect on biomass output was evaluated. For the evaluation of the temporal variability effect on the simulation results, measurement data for Ksat and saturated water content (considered to be equal to porosity) as measured at 15 DAS, 45 DAS and 90 DAS were used. The other parameters like water content at field capacity and at permanent wilting point were kept constant and set equal to values determined in 2010 (Van Elsacker, 2011). This assumption is justified since our measurements demonstrated that MatPOR at -10 kPa was not subjected to temporal variation. If MatPOR at -10 kPa, which corresponds to the water content at a matric potential of -10 kPa, does not change with time, water content at lower matric potentials like -33 kPa (field capacity) or -1500 kPa (wilting point) will not change either (Jury and Horton, 2004).

3.5.9.5. Simulation scenarios

A few scenarios are presented that allow evaluation of the temporal variability effect. These scenarios are intuitively chosen and the results are believed to be indicative for temporal variability effects. For the first scenario, the cropping season was divided in three parts. During simulation from 1 DAS to 15 DAS, the initial soil parameters as derived by Van Elsacker (2011) in 2010, which are displayed in APPENDIX II were used. For a simulation period of 16 DAS to 45 DAS, data obtained at 15 DAS were used, whereas for a simulation period of 46 DAS to 90 DAS, data for 45 DAS were applied. The layout of scenario 1 and the other scenarios is presented in Table 3.2. For scenarios 1, 2 and A, the top layer of the soil file was divided in depths of 0-20 cm, 20-45 cm. In scenarios 3, 4 and B, the top layer of the soil file was divided in layers of 0-10 cm, 10-20 cm, 20-30 cm and 30-45 cm because the data for saturated water content were available for these three upper depths, which thus better approximates reality. However, differences in the results obtained with scenarios 1,2 and A on the one hand and scenarios 3,4 and B on the other are negligible.

Table 3.2: Overview of the layout of the different scenarios used to evaluate temporal variability effect on simulation results in AquaCrop.

Data	*Scenario 1/3*	*Scenario 2/4*	*Scenario A/B,1*	*Scenario A/B,2*	*Scenario A/B,3*	*Scenario A/B,4*
Initial	1-15 DAS	1-7 DAS	1-90 DAS	-	-	-
15 DAS	16-45 DAS	8-30 DAS	-	1-90 DAS	-	-
45 DAS	46-90 DAS	31-72 DAS	-	-	1-90 DAS	-
90 DAS	-	73-90 DAS	-	-	-	1-90 DAS

4. RESULTS AND DISCUSSION

4.1. Variation in soil physical properties among season, time, rotation and depth

4.1.1. Bulk density

Measurements for the different test fields at the different moments during two growing seasons showed bulk density values within a range of 0.77-1.34 $Mg.m^{-3}$. For fine-textured soils, optimum bulk density for crop production is considered within a range of 0.9-1.2 $Mg.m^{-3}$ (Reynolds et al, 2007). Research by Khoa (2002) describes that for the Mekong Delta, rice yields are negatively influenced when soil bulk density reaches 1.35 $Mg.m^{-3}$. When BD values are lower than 0.9 $Mg.m^{-3}$ the soil becomes too loose to support standing of crops and thus compromising their growth. BD values higher than 1.2 $Mg.m^{-3}$ indicate that the soil is becoming more compacted. Compaction strengthens erosion effects and has a negative effect on crop root depth, water availability and aeration of the soil, resulting in a higher risk for crop failure and a reduction of plant growth. BD values were thus within the optimal range, as well as lower and higher than optimally required. Variability can be accounted to the different management techniques that were used (differences between treatments), the different times at which measurements were taken (within the season and between seasons) and the different depths at which the samples were taken. The importance of each factor in the explanation of total variability is displayed in Table 4.1. Depth and treatment are the most important factors for the explanation of the observed variability, representing 41% and 17% of the variation, respectively. Their interaction explained 23% of the variation. Temporal variability appeared to be limited, at least much smaller than that of treatment or depth.

Table 4.1: Variance components of the bulk density (level of significance is 0.01): cropping season (Season), time dynamics (Time), treatment type (Treatment), depth in the soil (Depth) and interactions between these components.

Effect	
Season	1%
Time	1%
Treatment	**17%**
Depth	**41%**
Season*Time	NS[a]
Season*Treatment	0.6%
Season*Depth	0.8%
Time*Treatment	NS
Time*Depth	0.9%
Treatment*Depth	**23%**

Numbers indicate the percentage in the explanation of the bulk density variance.

[a] not significant at the 0.01 level.

The variance due to the difference in season (winter-spring WS or summer-autumn SA), although small, can be explained by the fact that different crops are grown on the field for different seasons. At the one hand rice is grown, requiring puddling of the soil. On the other hand upland crops are cultivated that require less water and do not grow in paddy soils. The WS season (November-February) is considered as the first season in the rotation system, with rice being cultivated for all six treatments. In the following SA season, different crops are cultivated on the different field plots, according to the treatment method applied on this plot. For the field plots representing treatment 1 (rice-rice-rice) and treatment 2 (rice-rice-rice+OM), rice is the cultivated crop for both WS and SA. On the other fields, representing treatment 3 (rice-maize-rice), treatment 4 (rice-maize-rice+OM), treatment 5 (rice-mungbean-rice) and treatment 6 (rice-mungbean-maize), the cultivated crop during WS is rice, whereas for SA upland crops are cultivated (T3 and T4: maize; T5 and T6: mungbean). However, the seasonal factor seems to have very little influence on bulk density values measured in the soil and accounts for only 1% of the observed variation. Bulk density values for WS are found within a range of 0.79-1.34 $Mg.m^{-3}$, whereas for SA a similar result was found, with values between 0.77-1.35 $Mg.m^{-3}$. The small amount of seasonal variability can be explained by the fact that the field is prepared before the beginning of each growing season and can thus be considered to be very similar at the start of each season.

However, once the crops are sown, bulk density – and soil physical parameters in general - undergo changes that are no longer totally controlled by the farmer, resulting in within-season temporal variability. During WS, BD values were found within a range of 0.78-1.31 $Mg.m^{-3}$ at 15 DAS, 0.84-1.34 $Mg.m^{-3}$ for 45 DAS, and 0.89-1.33 $Mg.m^{-3}$ at 90 DAS. For SA, again similar results were found, with BD values within a range of 0.77-1.33 $Mg.m^{-3}$ at 15 DAS, 0.83-1.33 $Mg.m^{-3}$ for 45 DAS, and 0.89-1.35 $Mg.m^{-3}$ at 90 DAS. These values imply that bulk density increases with time during the growing season, as illustrated in Figure 4.1 for different depths during WS. Especially at the lower BD boundary, this increase is observed, whereas at the upper BD boundary no significant increase is observed. Moreover, the within-season temporal variability in bulk density is only significant in the top 10 cm and for the rice-rice-rice treatment methods (T1 and T2). Bulk density values increase with time from 0.79 to 0.91 $Mg.m^{-3}$ for treatment 1 and from 0.78 to 0.91 $Mg.m^{-3}$ for treatment 2. This corresponds to the increase that was observed for the lower boundary of BD values as stated earlier. Results for the SA season show the same absence of temporal variability for the deeper soil layer. However, in the top 10 cm, temporal variability can also be observed for T3, T4 and T5. No significant temporal variability was observed for T6, as illustrated in Figure 4.2. The presence of temporal variability at the top layer might be explained by the fact that this layer is more exposed to external influences such as impact of rain drops, the fact that it will be the first part of the soil to dry and that a greater part of the roots are present in this top layer and for a longer time, thus having a stronger influence.

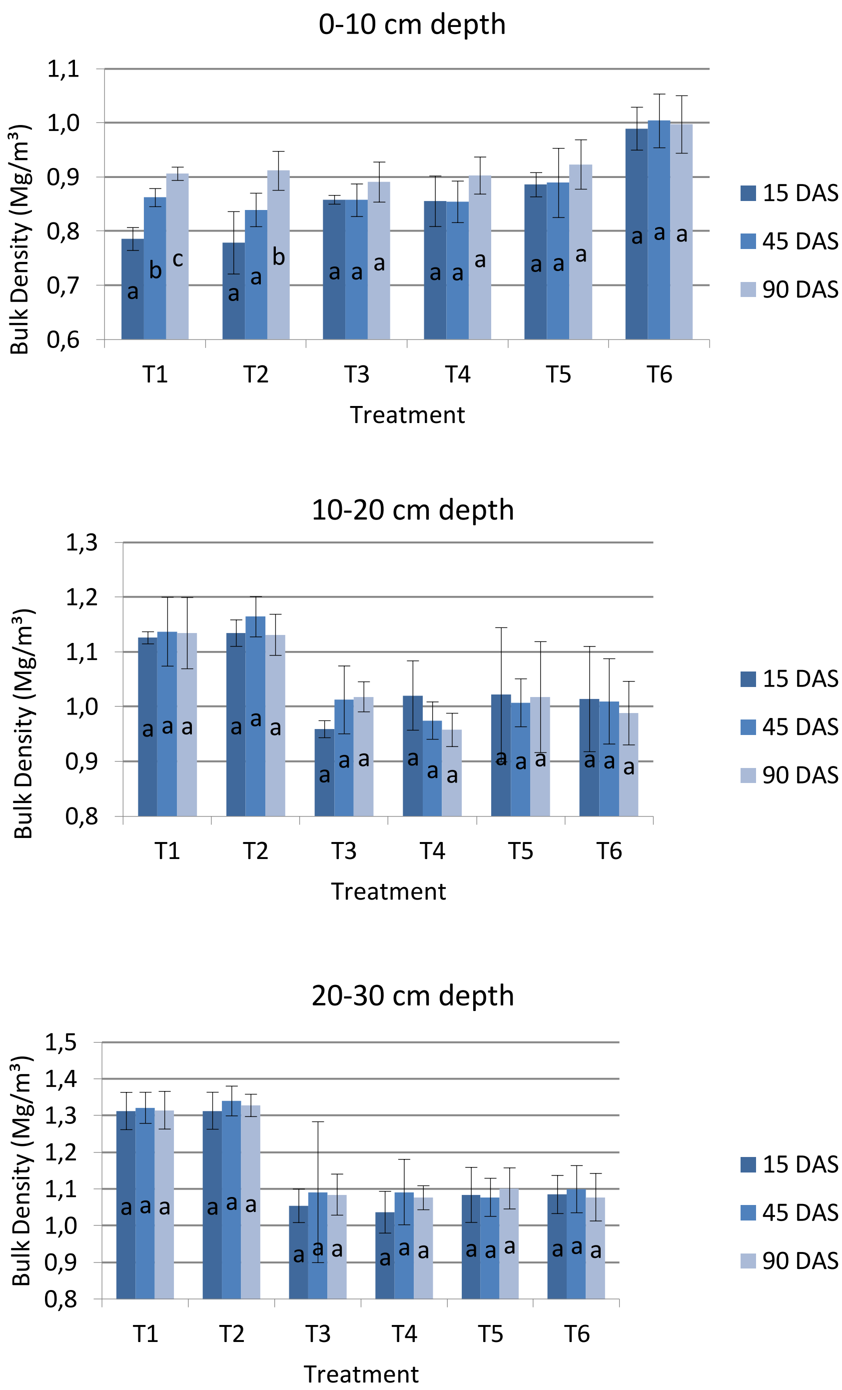

Figure 4.1: Impact of time (DAS = Days After Sowing) on bulk density for six treatments at depths of 0-10 cm (top panel), 10-20 cm (middle panel) and 20-30 cm (lower panel) during the WS growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at $p \leq 0.05$ using DMRT; a, b, c are the significant differences between depths.

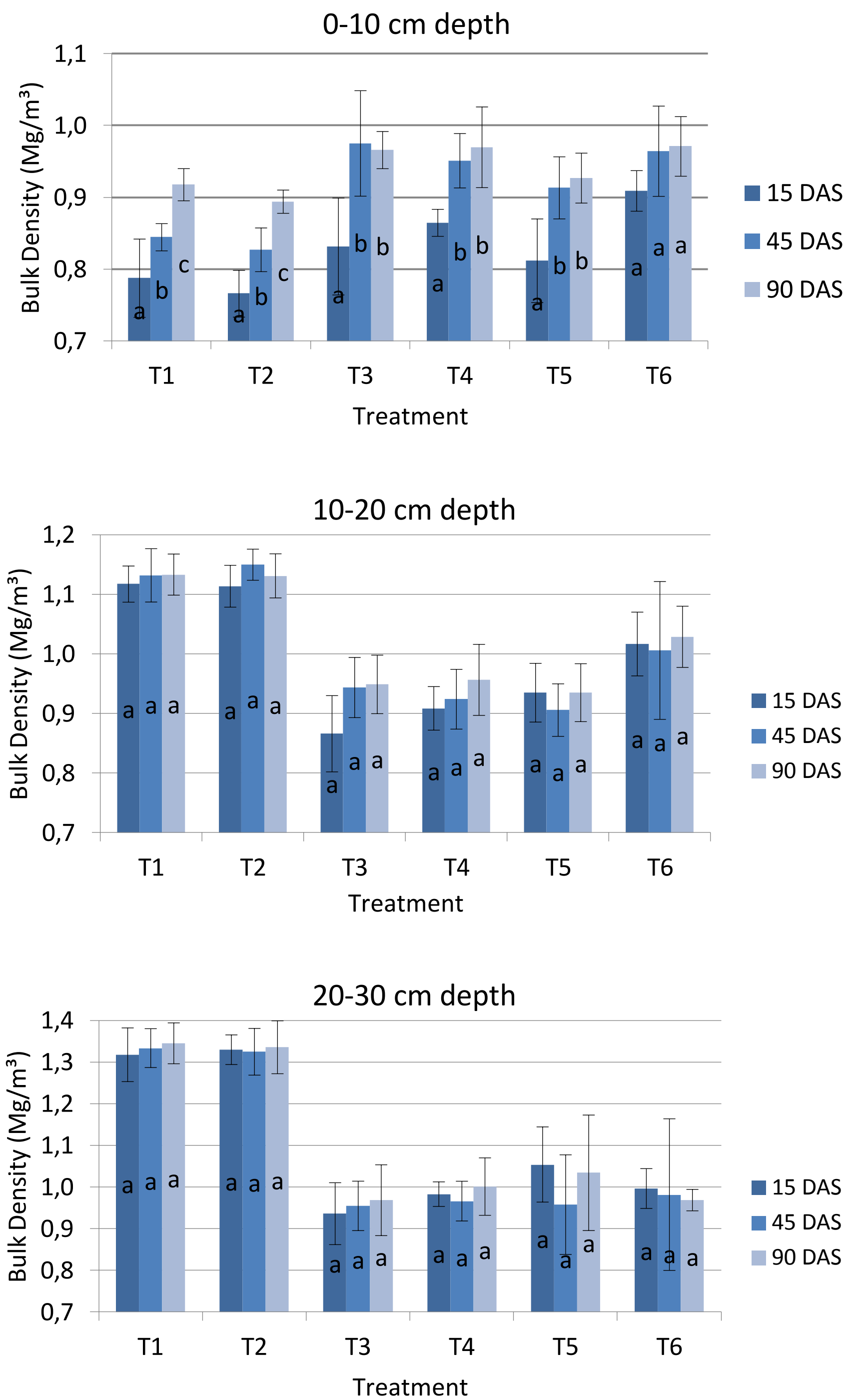

Figure 4.2: Impact of time (DAS = Days After Sowing) on bulk density for six treatments at depths of 0-10 cm (top panel), 10-20 cm (middle panel) and 20-30 cm (lower panel) during the SA growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at p ≤ 0.05 using DMRT; a, b, c are the significant differences between times.

Generally the most significant differences can be observed when comparing the rice rotation systems (treatments 1 and 2) on the one hand and rice-upland crop rotation systems (treatments 3 to 6) on the other hand. Similar observations were made by Van Elsacker (2011) who studied in 2010 the effect of treatment in combination with depth for this particular study area, without however taking the temporal factor into consideration. During WS season, the rice-rotation systems showed lower BD values in the top layer, but these were increasing with time during the growing season. Treatment 6, where two upland crops are cultivated during a year, shows highest bulk density values for the upper 10 cm. At 10-30 cm depth, the reverse is observed. Bulk density values for T1 and T2 are significantly higher than the values for T3 to T6. Bulk density values for T1 and T2 tend to exceed the upper limit of optimal bulk density at a depth of 20-30 cm, whereas for T3 to T6 bulk density values stay within the optimal range of 0.9-1.2 $Mg.m^{-3}$.

The effect of treatment system and depth is closely linked. Soil bulk density shows a significant increase with depth for the rice-rotation system, as shown in Figure 4.3. This increase is also observed for the upland-crop rotation systems but the differences were smaller and not always significant. For a depth of 0-10 cm, values between 0.78 and 1.0 $Mg.m^{-3}$ were measured during the WS season. At a depth of 10-20 cm bulk density was higher, with values ranging from 0.96 to 1.16 $Mg.m^{-3}$. Finally, at a depth of 20-30 cm, bulk density was generally found to be highest, with values varying between 1.04 and 1.34 $Mg.m^{-3}$. It should be noted that Figure 4.3 presents similar results as Figure 4.1, though the letter refer now to statistical differences with depth rather than with time.

The interaction between treatment and depth for bulk density, accounting for 23% of the variability of the results can be explained by the strong variability and increase of BD for treatments 1 and 2 on the one hand and the much weaker increase (15 DAS) and absence (45 and 90 DAS) of variability with depth for the treatments 3 to 6. This is again the effect of a more shallow plow layer for treatments 1 and 2 and deeper tillage, resulting in a deeper and more intense mixing of the soil under treatments 3 to 6.

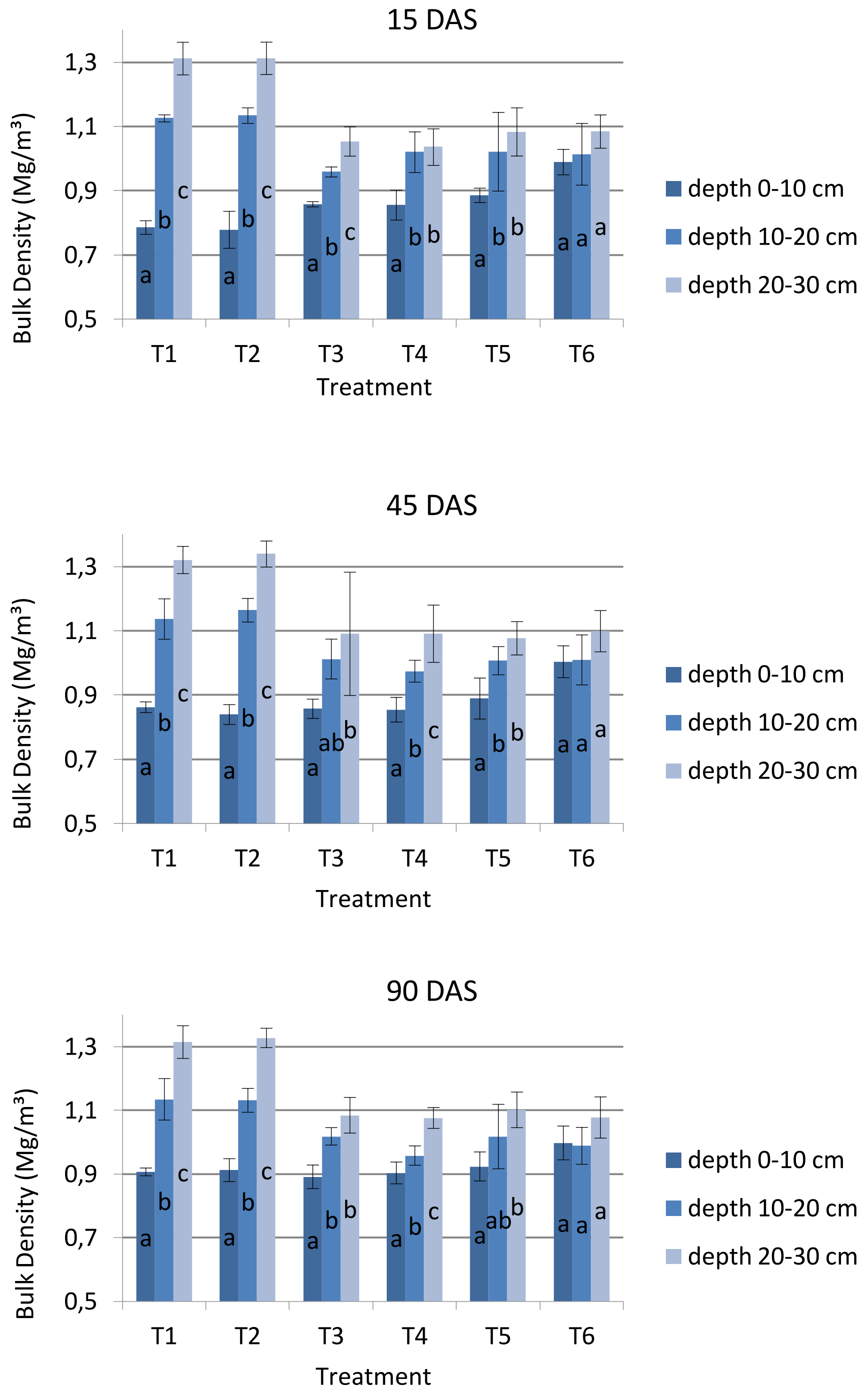

Figure 4.3: Impact of depth on bulk density for six treatments at 15 (top panel), 45 (middle panel) and 90 days after sowing (lower panel) during the WS growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at $p \leq 0.05$ using DMRT; a, b, c are the significant differences between depths.

This trend of increasing bulk density with depth can be found for most cases. Treatments 1 and 2 show significant differences between the values measured at the three different depths. Bulk density values for these rice rotation treatments reach values at a depth of 10-20 cm that are equal or higher than those values found at the 20-30 cm layer for the treatment systems with rice and upland crop rotation. This can be an indication of a more shallow position of the plow layer for these two treatments as a result of the shallow plowing and continuous rice cultivation. Treatments 3 to 5 show a weaker and more gradual increase and the bulk density at a depth of 10-30 cm is generally lower than for treatment 1 and 2. For treatment 6 no significant increase of bulk density with depth was found. These results can again indicate the difference of depth of the compacted plow layer for the rice-rice-rice rotation and the rotation with upland crops.

In the SA season a similar trend was found for the rice rotation treatments (see Figure 4.4). Bulk density showed a significant increase with depth for the measurements at 15 DAS, 45 DAS and 90 DAS. No significant differences were found at the different depths for the treatments with rice and upland crop rotation at 15 DAS, 45 DAS and 90 DAS, apart from a few small exceptions (T4, T5 and T6 at 15 DAS). This difference between SA and WS can be a consequence of the difference in crops grown during these seasons. In the SA growing season, rice is cultivated on paddy soils for the treatments 1 and 2. For treatments 3 to 6 upland crops are cultivated on soil bunds, which creates a disturbance of the top layer. For treatment 3 and 4 maize is cultivated and for treatment 5 and 6 mungbean is cultivated. It is found that under upland crop cultivation at 45 DAS and 90 DAS, BD values are within the optimal range of 0.9 and 1.2 $Mg.m^{-3}$.

BD values for treatment 1 and 2 at a depth of 20-30 cm are greater than 1.3 $Mg.m^{-3}$ for the three measurement moments of both the WS and SA season and are thus approaching the critical value of 1.35 $Mg.m^{-3}$ for rice cultivation in the Mekong Delta as described by Khoa (2002). For the upper 10 cm it was found that at 15, 45 and even 90 DAS, BD values are below the lower limit of 0.9 $Mg.m^{-3}$. This can indicate that rice yields will be negatively influenced throughout the entire growing season in the case of treatments 1 and 2. For the treatments 3 to 5 it is found that BD values are generally below the critical limit of 0.9 $Mg.m^{-3}$ at 15 DAS and 45 DAS in WS for depths of 0-20 cm but fall within the optimal range at 90 DAS. BD values for T6 are within the optimal range for the entire depth and during the entire growing season. During SA a similar result is found for BD values of T3-T6 at 15 DAS. At 45 DAS and 90 DAS of the SA season all BD values are found within the optimal range. These findings correspond with results in Van Elsacker (2011), who found that for the rice monoculture treatments yields were decreasing over a five-year period, whereas for the rotation systems with upland crops, yields were increased over that same period.

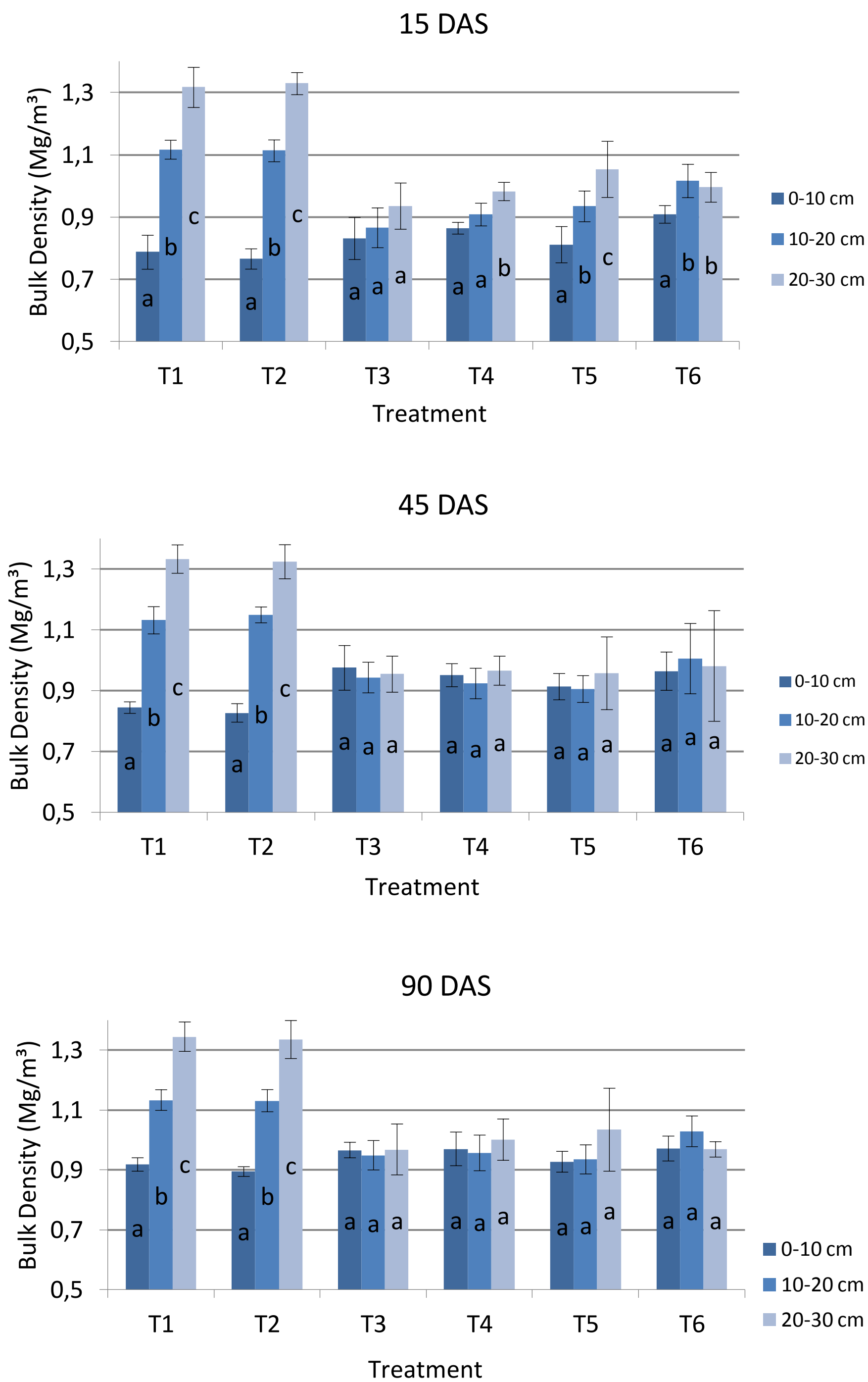

Figure 4.4: Impact of depth on bulk density for six treatments at 15 (top panel), 45 (middle panel) and 90 days after sowing (lower panel) during the SA growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at $p \leq 0.05$ using DMRT; a, b, c are the significant differences between depths.

Generally, the increase of bulk density with depth can be explained by the presence of a plow layer as indicated in section 3.3. Measurements were taken up to the plow layer, which is generally considered to be at a depth of 20-30 cm in paddy rice fields. The plow layer is characterized by higher bulk density and lower pore volume as an effect of compaction of this soil layer. For the rice monoculture treatments generally higher BD values are found at a more shallow depth compared to the treatments that include upland crops in the rotation system. Especially at the depth of 20-30 cm BD values are found that exceed the ideal range of 0.9-1.2 $Mg.m^{-3}$ for fine-textured soils. For rice cultivation preferred BD values are generally higher compared to those for upland crop cultivation. In that aspect it is not said that values exceeding 1.2 $Mg.m^{-3}$ will lead to crop failure. However, the values that are found for T1 and T2 at 20-30 cm depth are close to 1.35 $Mg.m^{-3}$, a value that -even for rice production- is too high and will lead to crop failure. This can be linked to the compacted layer, where bulk density value becomes so high that roots are no longer able to penetrate it and are thus compromised to grow to their optimal and full potential. For T3 to T6, BD values are generally found within the optimal range, never exceeding the upper limit of 1.2 $Mg.m^{-3}$. Although a plow layer is present because it is fundamental for rice cultivation, this layer will be found deeper in the soil, thus not compromising root growth.

Results for temporal variability showed less significance than was expected. Research by Alletto and Coquet (2009) in Southern France, for maize cultivation on loamy soils showed significant temporal variability throughout the growing season. Results showed that the temporal factor was responsible for up to 70% of the total variability, which is in strong contrast to our findings (1%). This might be due to a larger influence of environmental factors. Whereas for rice cultivation the field is flooded most of the time, reducing weed growth, erosion, impact of raindrops and repeated drying and wetting, maize fields in France are more susceptible for these influences. This can also be the explanation for the different temporal trend that is observed for T3 to T6 in WS and WS. During WS temporal variability is absent for T3 to T6. The cultivated crop is rice. However, during SA minor temporal variability effects are present for the upper soil layer. The cultivated crops are maize (T3 and T4) and mungbean (T5 and T6). These crops are grown on soil bunds and not under flooded conditions and might therefore be again more susceptible for environmental factors. These results thus suggest that temporal variability is less under rice cultivation. However, for T1 and T2 temporal variability of BD is present under rice cultivation.

Also the soil texture of the experiment described by Alletto and Coquet and the one described in this thesis is different. It is possible that loamy soils are more susceptible to temporal variability than clayey soils. The interaction between soil texture and temporal variability is something that could be interesting for future research.

4.1.2. Soil porosity

As presented in **Table 4.2**, variance in the results of total porosity of the soil is mostly explained by the factor depth and treatment, and their combined effect.

Table 4.2: Variance components of the total porosity (level of significance is 0.01): Cropping Season (Season); time dynamics (Time), treatment type (Treatment), depth in the soil (Depth) and interactions between these components.

Effect	
Season	NS
Time	3%
Treatment	**35%**
Depth	**14%**
Season*Time	NS
Season*Treatment	NS
Season*Depth	NS
Time*Treatment	NS
Time*Depth	2%
Treatment*Depth	**24%**

Measurements for our fields showed values within a range of 47% to 61%. Soil porosity is ideally about 50%, with around 25% stored water (Brady, 1998). For treatments 1 and 2, total soil porosity was significantly lower at a depth of 20-30 cm compared to the values found for depths of 0-20 cm. At a depth of 20-30 cm, porosity values for treatment 1 and 2 are in a range of 49.3-49.9% (WS) and 46.6-48.8% (SA), whereas the porosity values for the other treatments lie within a range of 56.9-58.9% (WS) and 57.5-60% (SA), a difference of up to 10%. For depths of 0-20 cm, variances between the treatments are less significant and lie within a range of 54.2-59.8%(WS) and 53.7-61.3% (SA). The effect of depth at 15 DAS in WS is displayed in Figure 4.5. Results for SA and at 45 DAS and 90 DAS are similar. Since porosity is linearly related to BD, the observed trends are similar.

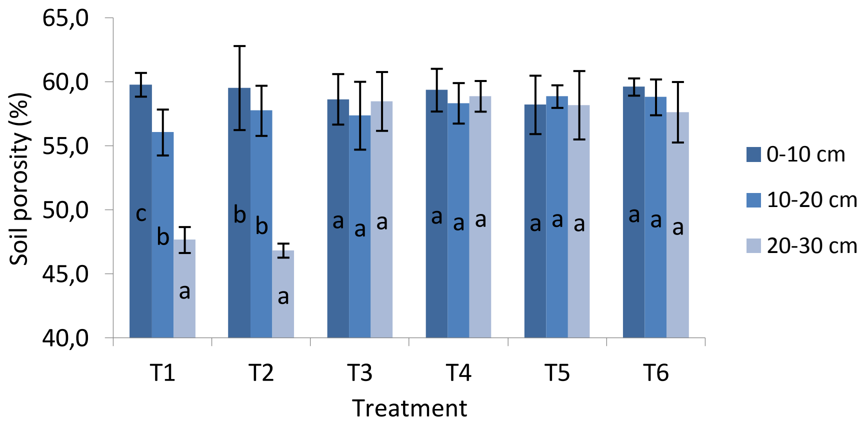

Figure 4.5: Impact of depth on total porosity for six treatments at 15 days after sowing (DAS) during the WS growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at p ≤ 0.05 using DMRT; a, b, c are the significant differences between depths.

Temporal variability was limited (not shown). The ranges of porosity for the different depths were slightly wider for SA compared to WS but the values show no significant differences. Within seasonal variability was more significant. For the rice-rotation systems total porosity shows a small decrease during the growing season in the top 20 cm and a small (but insignificant) increase in time was observed for the 20-30 cm horizon. In the upland crop rotation systems, total porosity showed a decrease from 15 DAS to 45 DAS and an increase from 45 DAS to 90 DAS. This trend is visual on the majority of plots but the differences are insignificant. Differences are visible for SA but no clear trend is observed. Generally, soil porosity was lower at the end of the growing season but can show a constant decrease as well as a decrease followed by an increase.

Differences between treatments are again most clear for the rice rotation treatments at the one hand and the upland crop systems on the other hand. For the top 20 cm little differences are present between the treatments. At a depth of 20-30 cm, soil porosity was significantly lower for T1 and T2, compared to the other treatments where upland crops are also cultivated. This is again an indication of the presence of the plow layer as the result of compaction at a more shallow depth due to the monoculture of rice.

4.1.3. Matrixporosity and macroporosity

Matrix porosity (MatPOR) was determined for different matrix potentials of -1 kPa, -5 kPa and -10 kPa. These matrix potentials define macro-pores greater than 300 µm, 60 µm and 30 µm respectively. In WS season, $MatPOR_{-1\ kPa}$ lie within a range of 0.44 and 0.54 $m^3.m^{-3}$, $MatPOR_{-5\ kPa}$ within a range of 0.43 to 0.53 $m^3.m^{-3}$ and $MatPOR_{-10\ kPa}$ between 0.42 and 0.52 $m^3.m^{-3}$. In SA season, $MatPOR_{-1\ kPa}$ was within a range of 0.44 and 0.55 $m^3.m^{-3}$, $MatPOR_{-5\ kPa}$ within a range of 0.43 to 0.56 $m^3.m^{-3}$ and $MatPOR_{-10\ kPa}$ between 0.42 and 0.52 $m^3.m^{-3}$. This indicates little temporal variation between the two seasons. The fraction of pores smaller than 30 µm was about 83-94% of total porosity, smaller than 60 µm 85-96% and smaller than 300 µm 87-97%, indicating a rather low amount of macro-pores. Likewise, $MacPOR_{-1\ kPa}$,

$MacPOR_{-5\ kPa}$ and $MacPOR_{-10\ kPa}$ varied between 0.013 and 0.073 m³.m^{-3}, 0.022 and 0.087 m³.m^{-3} and 0.034 to 0.101 m³.m^{-3}, respectively, for WS. Very similar values were observed for SA. Minimum or optimum values have not yet been defined for MatPOR and MacPOR. However, data from Carter (1988), Drewry et al. (2001), and Drewry and Patton (2005) suggest that for medium- to fine-textured soils, for the top 10 cm, MacPOR values higher than about 0.05 to 0.10 m³.m^{-3} is an indication for 'undegraded' soils, whereas values of MacPOR below 0.04 m³.m^{-3} indicate that the soil is 'degraded' as the effect of compaction or consolidation. This makes it difficult to draw conclusions with respect to the soil quality and if the occurring changes have a positive or a negative effect on soil quality.

Treatment and depth were again the main factors explaining variance of the results, whereas time showed a minor effect (Table 4.3). For the rice rotation systems, a decrease in MatPOR and MacPOR was observed with depth. For the treatment systems where upland crops are introduced, this decrease was limited or absent. This decrease is again an indication of compaction at a more shallow depth for the rice treatment systems. The decrease in MatPOR and MacPOR was most significant between 10-20 cm depth and 20-30 cm depth. The decrease between the 0-10 cm top layer and the 10-20 cm was not significant. These trends were found for both WS and SA. Figure 4.6 illustrates the effect of depth on MatPOR. Variability as a result of depth was less significant at the end of the growing season, at 90 DAS.

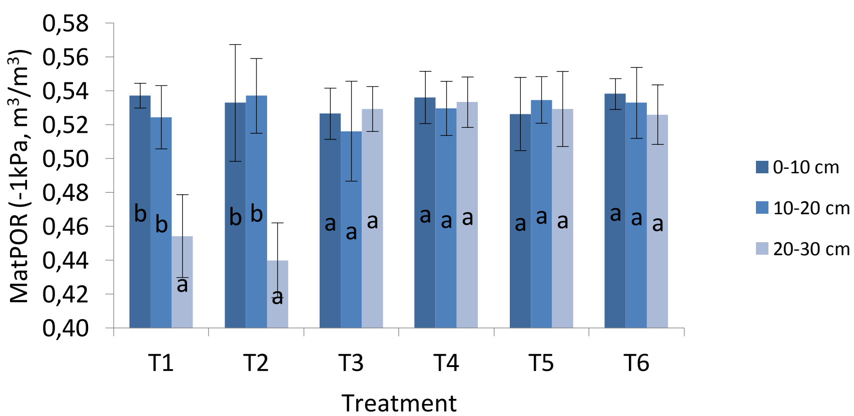

Figure 4.6: Impact of depth on MatPOR with matrix potential -1kPa for six treatments at 15 days after sowing (DAS) during the WS growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at p ≤ 0.05 using DMRT; a, b, c are the significant differences between depths.

Intra-seasonal temporal variability was present but small for MatPOR. Figure 4.7 shows a declining trend in $MatPOR_{-1\ kPa}$ and $MacPOR_{-1\ kPa}$ with time for the upper 10 cm. Similar results were found for MatPOR and MacPOR when -5 kPa and -10 kPa are taken as limits. No significant temporal variability was found for the deeper depths. The total difference between 15 DAS and 90 DAS in the upper 10 cm is significant for T1 but not for T2. The layer of 20-30 cm shows a small increase in MatPOR and MacPOR values. The rotation systems with the use of an upland crop show a decrease from 15 DAS to 45 DAS and an increase from 45 DAS to 90 DAS. This variability is not significant, with the exception of T5 in the SA season.

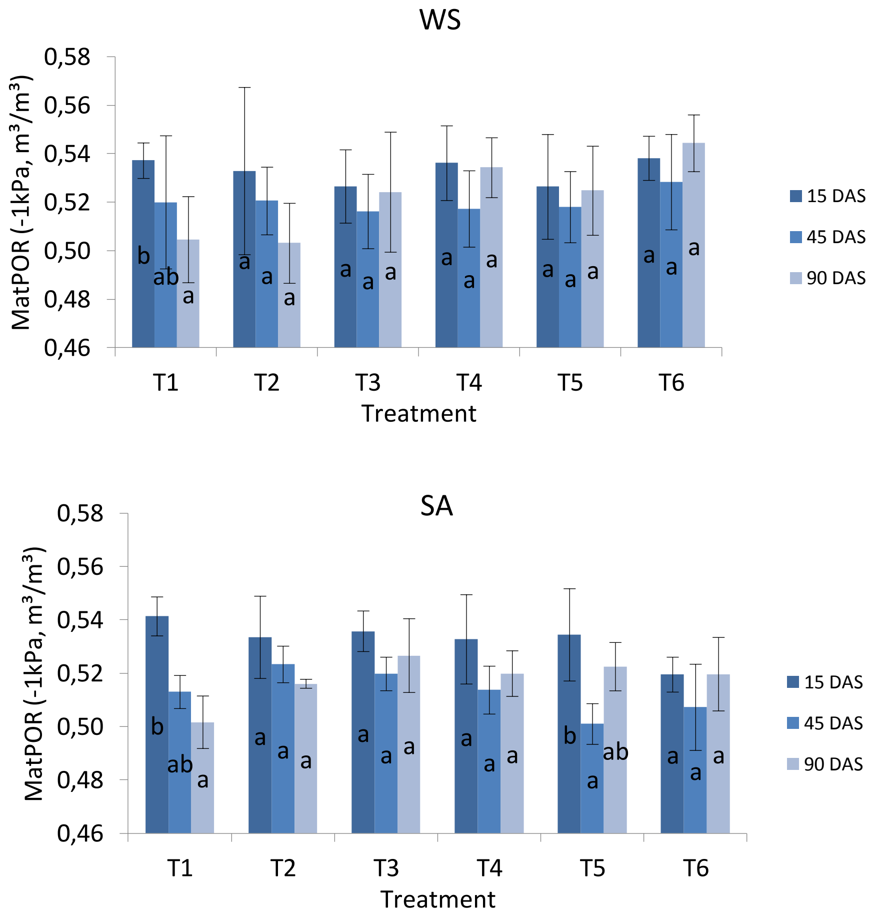

Figure 4.7: Temporal variability of MatPOR with matrix potential -1kPa for six treatments at a depth of 0-10 cm for WS and SA growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at p ≤ 0.05 using DMRT; a, b, c are the significant differences between times.

Table 4.3: Variance components of MatPOR with matrix potential of -1 kPa, -5 kPa and -10 kPa (level of significance is 0.01): Cropping Season (Season); time dynamics (Time), treatment type (Treatment), depth in the soil (Depth) and interactions between these components.

Effect	*MatPOR (-1 kPa)*	*MatPOR (-5 kPa)*	*MatPOR (-10 kPa)*
Season	NS	NS	NS
Time	2%	0.9%	NS
Treatment	**20%**	**20%**	**19%**
Depth	9%	8%	7%
Season*Time	NS	NS	NS
Season*Treatment	NS	NS	NS
Season*Depth	NS	NS	NS
Time*Treatment	NS	NS	NS
Time*Depth	NS	NS	NS
Treatment*Depth	**27%**	**28%**	**28%**

4.1.4. Infiltration Rate and Saturated Hydraulic Conductivity

Infiltration rate measurements were performed on the field at the soil surface only. No depth measurements were taken. Values for infiltration rate i ranged from 2.62×10^{-7} to 1.92×10^{-6} $m.s^{-1}$ in WS and from 3.41×10^{-7} to 2.30×10^{-5} $m.s^{-1}$ in SA, whereas saturated hydraulic conductivity Ksat varied between 4.87×10^{-8} to 3.59×10^{-7} $m.s^{-1}$ in WS and from 6.35×10^{-8} to 4.35×10^{-6} $m.s^{-1}$ in SA. Ksat values calculated with the equation of Reynolds and Elrick (1990) were 5.3 times larger than i values 5 h after the start of the infiltration experiment. This confirms what is stated in Reynolds and Elrick in Dane and Topp (2002). They say that q_s is often substantially greater than K_{fs}, dependent on the values of H, d, a and α^*. It is found that especially α^* has an influence of the magnitude of the difference. For $\alpha^* = 0.01$ cm^{-1} it was found that q_s/K_{fs} is 5.7, which is close to the value of 5.3 that was found for our results. However, as stated in Elrick *et al*. (1989), α^* values are not exact and thus leading to possible deviation from the true values. In the remainder of this section, we will continue working with Ksat.

Table 4.4 gives an overview of the importance of each factor in the explanation of the variability of Ksat. The results show the importance of the factor season, which was absent for the other parameters. Also within-season variation (time) greatly affected the variation in Ksat, and the interaction with season. Treatment was least responsible for differences in Ksat.

Table 4.4: Variance components of saturated hydraulic conductivity Ksat (level of significance is 0.01): cropping Season (Season); time dynamics (Time), treatment type (Treatment), depth in the soil (Depth) and interactions between these components.

Effect	
Season	**23%**
Time	**18%**
Treatment	13%
Season*Time	**16%**
Season*Treatment	10%
Time*Treatment	6%

The significant differences in Ksat between the two growing seasons, is mainly attributed to the treatment with upland crops, where Ksat values differed significantly between the seasons. For the rice-rice-rice treatments no significant differences were found between WS and SA. This is illustrated in Figure 4.8 for 15 DAS. Similar results were found at 45 DAS and 90 DAS For T1 and T2 rice is cultivated in WS and SA, but for T3-T6 rice is cultivated in WS and upland crops in SA. Soil bunds are introduced in the SA season. These soil bunds are necessary for the cultivation of upland crops, which do not grow optimally on puddled soils. The introduction of soil bunds results in a strong modification of the upper soil layer. Ksat values for treatments 3 to 6 were for SA up to 10 times higher compared to those for WS. With values ranging from 4.41×10^{-7} to 4.35×10^{-6} $m.s^{-1}$, they are close to optimal values of 5×10^{-6} to 5×10^{-5} $m.s^{-1}$ as suggested by Reynolds *et al*. (2003). This range is frequently considered to be 'ideal' for agricultural soils with respect to promoting rapid infiltration and redistribution of water for crop production, reduction of surface runoff and soil erosion, and promoting relatively rapid drainage of excess soil water. Values above this range indicate droughtiness as an effect of too rapid infiltration and drainage to allow adequate water sorption into the soil matrix. Values below this range, as was generally found for our results, may cause reduced trafficability and excessive ponding, runoff, erosion and water-logging of the root zone. It should be noted however that the suggested optimal range is based on Ksat measurements on undisturbed soil samples in a water tank under laboratory conditions, whereas we measured Ksat with a ring infiltrometer. As observed by Reynolds *et al.* (2000) for fine-textured soil, ring infiltrometer methods result in Ksat values that are smaller than those obtained from undisturbed cores. This might suggest that the values we observed for T3-T4 in SA are close to or within the optimal range.

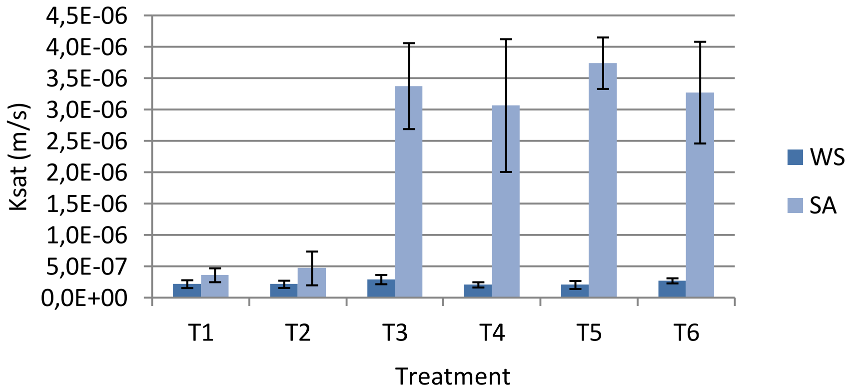

Figure 4.8: Temporal variability of saturated hydraulic conductivity Ksat between two growing seasons for six different treatments. WS = winter-spring season; SA = summer-autumn season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations.

In contrast with bulk density and porosity, Ksat showed significant temporal variability within the growing season (Figure 4.9). A significant decrease is observed for treatments 1, 2 and 3 during the WS season. Treatments 4, 5 and 6 do not show significant temporal variability in the WS season. A clear temporal variability is observed for all treatments during the SA season, with Ksat showing a decrease with time. The decrease between 15 DAS and 90 DAS is significant but the major decrease occurs in the period between 15 DAS and 45 DAS. The variability effect during SA is much stronger for Ksat under maize (T3 and T4) and mungbean (T5 and T6) cultivation in comparison with the temporal variability effect under rice cultivation for T1 and T2. Temporal variability of K and Ksat was also found in Alletto and Coquet (2009) for maize cultivation on loamy soils and by Hu *et al.* (2009) for different land uses (no data for rice cultivation) on sandy loam soils. These findings suggest that temporal variability with respect to hydraulic conductivity is present and should be considered. The findings also suggest that this temporal variability effect is more significant under upland crop cultivation and less significant under rice cultivation.

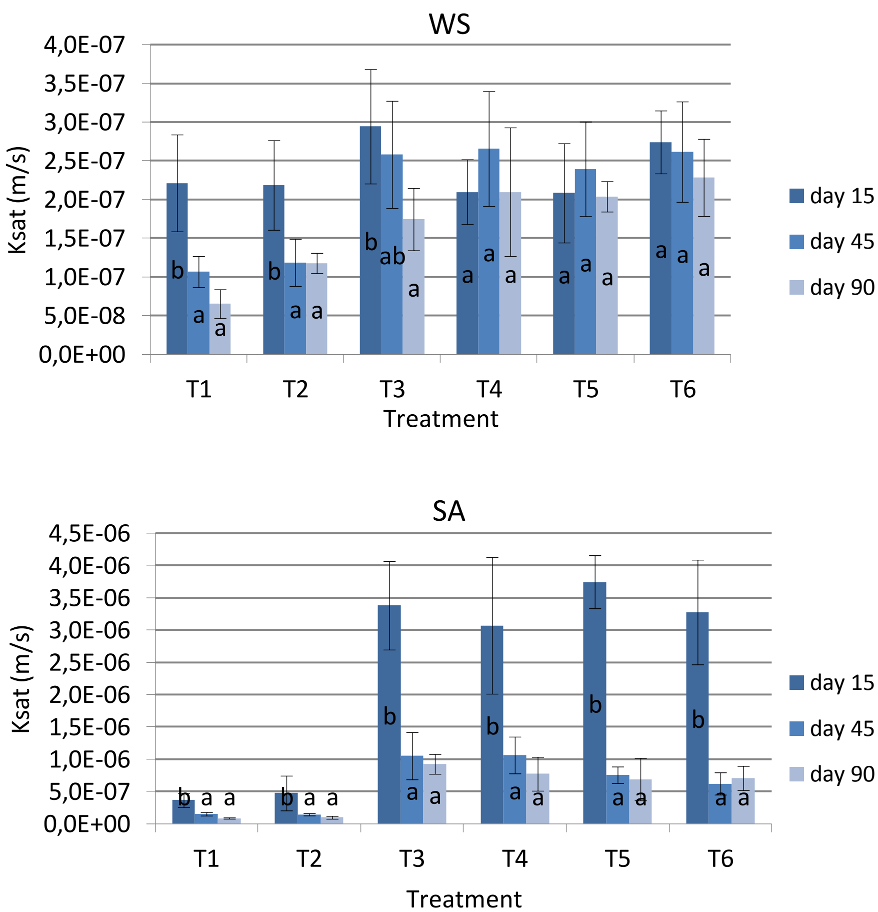

Figure 4.9: Temporal variability of saturated hydraulic conductivity Ksat for six treatments within WS and SA growing season. T1 = rice-rice-rice rotation; T2 = rice-rice-rice rotation + 10 tons organic manure/crop season; T3 = rice-maize-rice rotation; T4 = rice-maize (+ 10 tons organic manure) –rice rotation; T5 = rice-mungbean-rice rotation; T6 = rice-mungbean-maize rotation. Vertical error bars represent standard deviations. Different letters in each column show statistically significant differences at $p \leq 0.05$ using DMRT; a, b, c are the significant differences between times.

4.2. Predicted rice biomass and yield

4.2.1. Calibration of rice

The simulated soil water content was most dependent on the initial soil data inserted in AquaCrop and the irrigation scheme presented. After a small calibration to improve the irrigation scheme, simulation results were similar to the observed data. When calibration was performed with respect to canopy cover and biomass (canopy development), soil water content stayed more or less constant throughout this process. Table 4.5 summarizes the values found for observed and simulated canopy cover, biomass and soil water content after calibration for this treatment.

Table 4.5: Overview of the simulated and observed data for canopy cover, biomass and soil water content (0,2 m depth) for Treatment 1.

	Canopy cover (%)		Biomass (ton.ha^{-1})		Soil water content (mm)	
DAS	Field	Simulated	Field	Simulated	Field	Simulated
15	5,8	5,9	0,71	0,136	109,5	116,8
30	17,5	40,3	2,86	1,026	118,7	116,0
45	71,3	77,1	4,58	3,459	108,9	101,4
60	81,3	77,9	5,60	5,716	119,0	114,6
90	71,3	71,1	10,50	10,800	101,6	91,3

Figure 4.10 shows the change of measured and simulated SWC with time as found for calibration for treatment 1. Soil water content appears to vary strongly in time as an effect of irrigation and percolation, and evapotranspiration. A good fit was obtained by improving the irrigation scheme. This, however, means that the irrigation scheme is different from the actual irrigation scheme that was applied during the growing period. Calibration of the model for soil water content had very limited influence on simulation results for canopy cover and biomass.

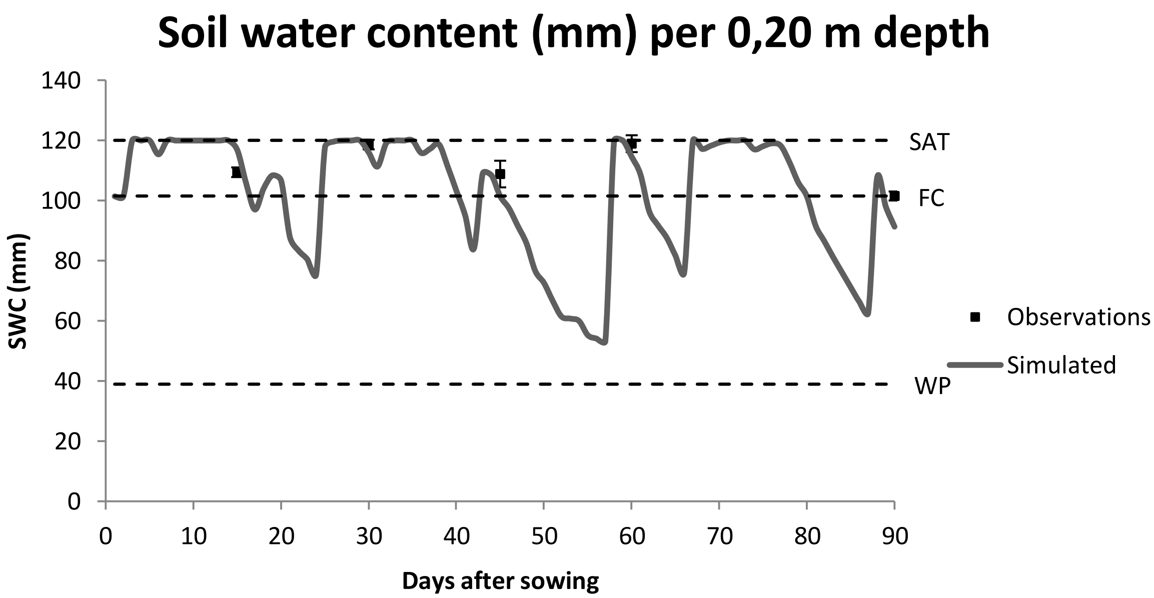

Figure 4.10: Variation of measured and observed soil water content (mm) at a depth of 0-20 cm over time (days after sowing).

Calibration for canopy cover was difficult and negatively affecting simulated biomass. These difficulties can be ascribed to the fact that the measurement technique was a rather robust method and results are thus rather indicative. During the calibration, we tried to get compromise between obtaining an optimal trade-off between goodness-of-fit statistics for canopy cover and for biomass. The observed and simulated canopy cover and biomass as a function of time are plotted in Figure 4.11 and Figure 4.12, respectively.

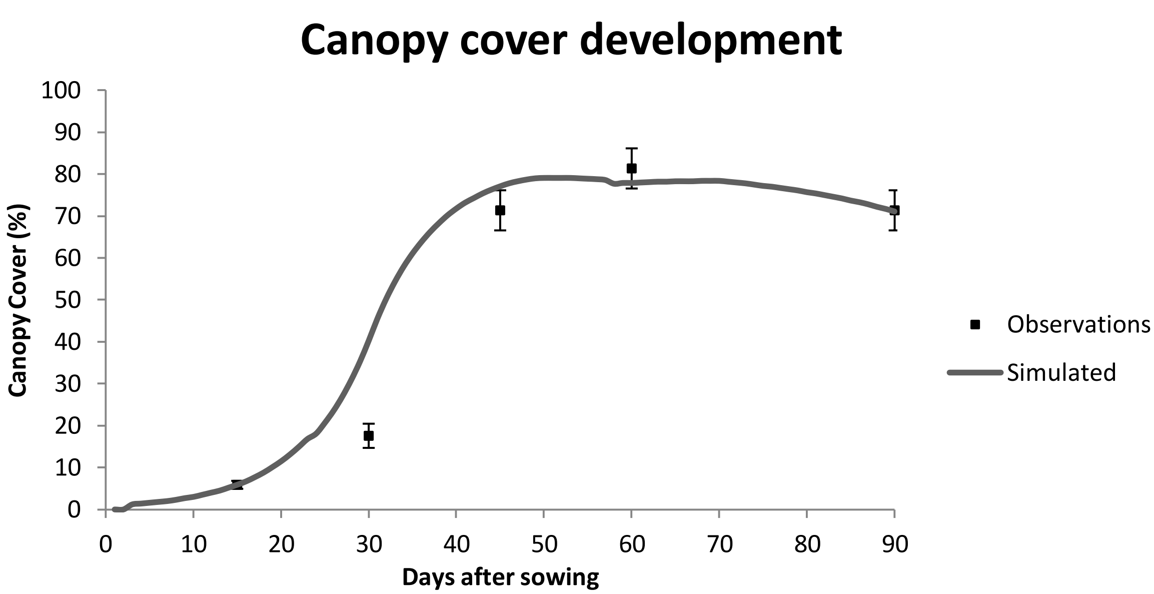

Figure 4.11: Evolution of measured and observed rice canopy cover (%) over time (days after sowing) during the WS growing season.

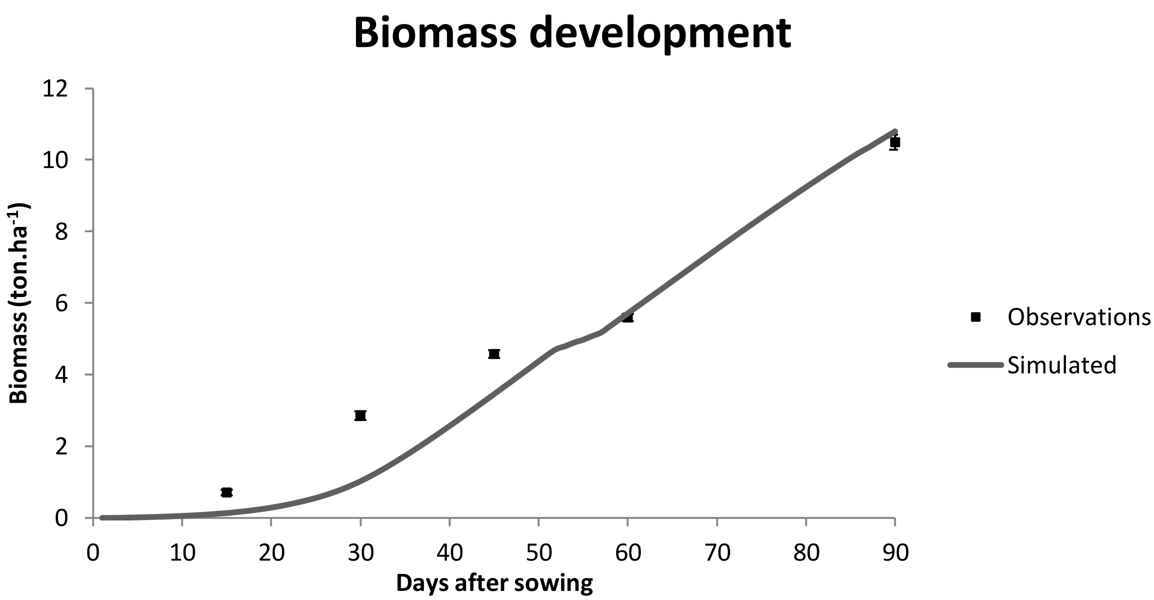

Figure 4.12: Evolution of measured and observed rice biomass (ton.ha^{-1}) over time (days after sowing) during the WS growing season.

The statistical parameters that were found after calibration are given in Table 4.6. The parameters represent the calibration of Treatment 1 during WS season. Calibration for the other treatments gave similar results of best possible goodness-of-fit.

Table 4.6: Statistical parameters describing goodness-of-fit of the calibrated model for treatment 1 during the WS season. R^2 = coefficient of determination; RMSE = Root Mean Square Error; NMRSE = Normalized Root Mean Square Error; EF = Nash-Sutcliffe model efficiency coefficient; d = Willmott's index of agreement.

	Canopy Cover	*Soil Water Content*	*Biomass*
R^2	0.91	0.65	0.97
RMSE	10.6	6.5	1.005
NMRSE	21.5	5.9	20.7
EF	0.88	0.02	0.91
d	0.97	0.84	0.98

Values for R^2 range from 0 to 1, with values close to 1 indicating a good agreement. For canopy cover and biomass, values of R^2 are close to 1, indicating a good agreement between simulation results and the observations. R^2 values of soil water content indicate a moderate agreement. RMSE ranges from 0 to positive infinity. The closer to 0, the better the model performance. For NRMSE a simulation can be considered excellent if NRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30%. RMSE and NMRSE values in Table 4.6 indicate a moderate to fair fit for canopy cover and biomass simulations and an excellent fit for soil water content. EF can range from minus infinity to 1. An EF of 1 indicates a perfect match between the model and the observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction then the model. EF values for canopy cover and biomass estimation indicate a good fit of the simulated data with the observations, whereas, for the estimation of soil water content, the EF value indicates that the model results are only a slightly better estimation than the mean of the observation results. Finally, d ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data. Willmott's index of agreement indicates again a good fit for canopy cover and biomass simulation results and a decent fit for soil water content estimation.

Generally, calibration has led to a good fit of the results for canopy cover and biomass simulation and a good but slightly worse fit for simulation results with field data for soil water content development. However, results for soil water content are obtained using a modified irrigation scheme. The original irrigation scheme as obtained due to personal communication with the farmer was not fit to provide a good estimation.

4.2.2. Temporal variability effects

In order to evaluate the effect of temporal variability of the measured soil physical parameters, the porosity and Ksat values presented in section 4.1 were implemented in the simulation.

The different scenarios taken into account, it should be noted that, if temporal variability has an effect on the simulation results, results for simulated total biomass (and later for canopy cover, biomass and soil water content development) will differ less from the field data in those scenarios where the influence of initial soil parameters is the strongest because calibration was performed for these values. This is confirmed by the results. Scenarios A,1 and B,1 are the scenarios for which the model was calibrated. These scenarios give the best goodness-of-fit for canopy cover, biomass and soil water content throughout the growing season, and the simulated total biomass was closest to the measured biomass. The second best estimation was obtained with scenarios 1 and 3. Scenarios 1 and 3 take into account temporal variability, with the largest share and influence of the initial soil parameters. In scenarios 2 and 4, the share of initial values for which was calibrated is smaller and the simulation gave a slightly less goodness-of-fit for the results. The least results were obtained with the scenarios A,2/3/4 and B,2/3/4. These scenarios are entirely based on soil parameters at 15 DAS (A/B,2), 45 DAS (A/B,3) and 90 DAS (A/B,4) and the share of the initial values is zero. The absolute differences that were obtained between the results of the simulations and the observed values are presented in Table 4.7.

Table 4.7: List of the absolute differences *|Δ|* between the simulated total biomass at the end of the growing season in the reference scenario and that from the other scenarios.

scenario	*|Δ|*
A,1	0,0821
B,1	0,0821
1	0,0923
3	0,0958
2	0,1256
4	0,1287
A,3	0,2149
A,2	0,2174
B,3	0,2319
B,2	0,2696
A,4	0,3428
B,4	0,3468

In general, biomass results obtained with the different scenarios do not differ very strongly from the reference one. The result with the largest deviation from the observed values was found for scenarios A/B,4. Total biomass estimation for scenarios A/B,4 gave a value of 0.35 ton.ha^{-1} higher than what was measured in the field. Values around 13 ton.ha^{-1} were generally found for total biomass, which means that relative estimation errors for total biomass about 3%, which is very small.

Table 4.8, Table 4.9 and Table 4.10 show the goodness-of-fit statistics for the different scenarios for canopy cover, biomass and soil water content respectively.

Table 4.8: Overview of the statistical parameters obtained for canopy cover simulation, averaged over the six treatments, with respect to rice production in the WS season.

scenario	*r^2*	*RMSE*	*NMRSE*	*EF*	*d*
1	0,89	13,7	24,8	0,84	0,96
2	0,89	13,6	24,7	0,84	0,96
A,1	0,84	16,3	29,5	0,77	0,94
A,2	0,83	16,8	30,4	0,76	0,94
A,3	0,84	16,6	30,2	0,76	0,94
A,4	0,83	16,8	30,5	0,76	0,94

Results for canopy cover in Table 4.8 suggest that temporal variability of the soil physical parameters has very little effect on the statistical parameters for goodness-of-fit, and thus on the simulation result. However, scenarios 1 and 2, where temporal variability is explicitly implemented in the model, show slightly better goodness-of-fit statistics.

Table 4.9 shows a similar result with respect to biomass. Again, the effect of changes in the soil properties on biomass simulation is almost absent. This time, statistical parameters suggest a slightly better estimation for the scenarios where temporal variability is not explicitly included. The difference is very small, suggesting that temporal variability has no significant effect on biomass simulation. This corresponds with the results found for total biomass simulation.

The fact that biomass and canopy cover are not affected can be ascribed to the fact that no water stress occurs. This is the result of an extensive irrigation pattern due to the availability of sufficient irrigation water throughout the entire growing season. As long as water is available, threshold values for canopy cover and biomass are not exceeded and water stress does not occur, minimizing the effect of temporal variability effects of the soil physical characteristic.

Table 4.9: Overview of the statistical parameters obtained for simulated biomass, averaged over the six treatments, with respect to rice production in the WS season.

scenario	r^2	*RMSE*	*NMRSE*	*EF*	*d*
1	0,97	1,2	20,5	0,91	0,98
2	0,97	1,2	20,5	0,91	0,98
A,1	0,97	1,1	18,7	0,93	0,98
A,2	0,97	1,1	18,9	0,93	0,98
A,3	0,97	1,1	18,9	0,92	0,98
A,4	0,97	1,1	19,3	0,92	0,98

Results in Table 4.10 show that simulation of soil water content is dependent on the soil file. The scenarios that differ from the calibrated scenario give values of the statistical parameters indicating a lower goodness-of-fit, except for scenario A,2, which gives a very similar goodness-of-fit. This indicates that the soil properties have an influence on the correctness of the simulated result. If temporal variability occurs, the parameter values in the soil profile change, resulting in a change in soil water content development. Therefore, temporal variability should be taken into account in order to obtain a more accurate simulation result. The simulation result for soil water content is strongly dependent on the irrigation scheme and the soil profile. The irrigation scheme is considered to be a fixed scheme so the differences in simulation results found for soil water content are the effect of the temporal variability of the soil water profile. The parameter describing saturated water content in the soil is of great importance for the simulated result. This is especially the case for soils where rice is produced since water content is preferentially kept very high by flooding and thus close to the saturated soil water content.

Table 4.10: Overview of the statistical parameters obtained for simulated soil water content, averaged over the six treatments, with respect to rice production in the WS season. The line in bold indicates the parameters of the scenario for which the model was calibrated.

scenario	r^2	*RMSE*	*NMRSE*	*EF*	*d*
1	0,40	8,7	7,8	-0,59	0,67
2	0,68	13,7	12,3	-2,51	0,70
A,1	**0,65**	**6,2**	**5,5**	**0,37**	**0,87**
A,2	0,57	5,7	5,1	0,43	0,79
A,3	0,50	8,0	7,2	-0,40	0,68
A,4	0,26	10,1	9,1	-0,89	0,50

The results in Table 4.10 however do not show whether taking into account temporal variability improves the simulation results. Because calibration was performed for a fixed set of parameters, best simulation results were found for simulation with this set of parameters. Calibration with respect to SWC for this fixed set of parameters required alteration in the irrigation scheme, thus forming an incorrect irrigation scheme. The results show that variability of the considered soil properties leads to different simulation results. Taking this into account, it can be said that variability in soil properties (in this case as a function of time) should be taken into account in order to simulate soil water content more accurately. In order to evaluate the real effect of temporal variability, an evaluation method can be set up where the irrigation scheme is exact to the real scheme and the effect on goodness-of-fit for taking into account temporal variability is evaluated.

The arrangement of the irrigation scheme has a strong influence on simulation results of biomass, canopy development and soil water content simulation but was considered as a fixed scheme in this study. However, the correctness of the implemented irrigation scheme can be questioned since it was based on personal communication and might not match reality. Anyhow, the results show that SWC is greatly affected by the choice of the soil physical parameters. Since temporal variability is present and variability has an effect on simulation results, it can be concluded that including temporal variability in models might improve the correctness of the model and the simulation result.

Temporal variability effects on simulation for upland crops were not tested in this thesis since AquaCrop does not provide crop data for mungbean and no crop data was collected for mungbean and maize cultivation during the SA season at our experiment site. It is however possible that different results would have been found if biomass and canopy cover of upland crops would have been considered, particularly if irrigation was not optimal. Whereas for rice cultivation the soil water content is preferably kept close to saturation (flooding, extensive irrigation), arrangement of an irrigation scheme for upland crop cultivation is more difficult to obtain. Obtaining insight in temporal variability of soil physical characteristics under upland crop cultivation and including this in irrigation scheduling might therefore improve irrigation efficiency.

5. GENERAL CONCLUSION AND RECOMMENDATIONS

The results of the measurements for bulk density, matrix- and macroporosity, infiltration rate and hydraulic conductivity show a lot of variability. In case of bulk density, matrix- and macroporosity, the observed variation was mainly associated with treatment (crop rotation and management) and soil depth, whereas infiltration rate and hydraulic conductivity was most subjected to seasonal and interseasonal variability (depth was not considered for that property). The effect of treatment was mainly associated with distinct crop rotations: one with three successive rice growing seasons and one where upland crops were introduced in the rotation system. This observed variation could be explained by the more intense and deeper soil tillage practices, affecting the plow layer, in the rice monocultures.

Treatment also influenced the effect of the other variation defining factors (depth and time). An important difference was found in the variation of the soil properties with depth. The successive rice cultivation treatments showed a strong increase in bulk density, and a decrease in matrix- and macroporosity, with depth. This effect was smaller for the rotation systems with upland crops.

Soils for rice cultivation are puddled in order to increase bulk density and decrease hydraulic conductivity and macroporosity. This is important for water availability in order to meet the high water-demand of the rice crops. However, when puddling becomes too strong, these values exceed their optimum values and become too high (bulk density) or too low (porosity, hydraulic conductivity). Furthermore, repeatedly shallow tillage practices can cause the plow layer to become too shallow, hindering optimal root development and thus leading to a decrease of yield.

Our results show that those rotation systems in which at least one upland crop is introduced is the most preferential. However, a rotation system with two upland crops and one rice crop only seems might be less appropriate due to the importance of rice as food crop and source of income for the Vietnamese people. Since rotating with two upland crops did not result in significantly different physical soil properties compared to a rotation with only one upland crop, the latter might thus be preferred. Moreover, the cost of introducing upland crops in the agricultural system is higher than for rice. Therefore, the gain of introducing upland crops should outweigh their cost. This is possible for one upland crop but difficult for two as shown by Tran Ba *et al.* (2013).

The importance of temporal variability (in infiltration rate and hydraulic conductivity) was again dependent on the crop rotations, with two distinct crop rotations: rice monoculture and rotations with rice and upland crops. We found that during the winter-spring season temporal variability was strongest for the rice monoculture rotation systems. The rice monoculture systems display a similar trend for temporal variability during the summer-autumn season. However, for the rotations with rice and upland crops, SA is the season during which upland crops are cultivated. In contrast with the findings for WS and accordingly rice cultivation for these treatments, significant temporal variability in infiltration rate and hydraulic conductivity was found during SA. The greatest variance was found during the first half of the growing season. Significant variability was found between results for infiltration rate and hydraulic conductivity during WS and SA for the rotations with rice and upland crops. This variability effect can be ascribed to the difference in cultivated crop and thus the difference in preparation of the field.

In case of bulk density, matrix- and macroporosity, where temporal variability during both seasons is very limited, it was found that temporal variability, if present, was found for the upper soil layer and not for the deeper depths. This might be the result of a greater influence of the rice crop and of environmental factors for this upper soil layer.

Interesting for further research might be the evaluation of temporal variability as an effect of soil texture. It is not known whether temporal variability is similar for all soil types. The question may arise if temporal variability is present for each soil type. So far it has been found for clayey, loamy and sandy loam soils.

The presence of temporal variability also affected soil-water content and biomass simulated with the cropwater model AquaCrop, however only to a limited extent. The results showed that for a calibrated model, variation of the soil hydraulic parameters resulted in differences in simulated output and a small change in goodness-of-fit statistics of simulated soil water content with the measured values. This indicates that, although small, (temporal) variability has an effect on the simulation results and the correctness of these results. Most models do not take into account this temporal variability and simulation results might therefore be less accurate. When including temporal variability in a model, more exact results can be obtained, allowing arrangement of a more exact irrigation scheme.

Variability of soil hydraulic parameters had no significant effect on estimation of canopy cover and biomass development of the rice crops. This can be ascribed due to the fact that sufficient water for irrigation was available and the soil water content was held close to saturation as preferred for rice cultivation. Due to this high water availability during the growing season, no stress occurred.

For further research, it might be interesting to evaluate the effect of temporal variability on canopy cover, soil-water content and biomass production under upland crop cultivation. If significant effects are found, soil water content can be more accurately modeled, allowing arrangement of a more efficient irrigation scheme.

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APPENDIX I

Individual soil horizon description

Ap (0-20/25 cm): Distinguished by root distribution

The Ap horizon is characterized by very dark grayish brown (10YR 3/2) color for moist conditions and gray (10YR 5/1) when dry; the soil texture is clay at this depth; occurrence of many yellowish brown (10 YR 5/6) spots; massive; slightly sticky and plastic; ripe; few open, tubular, biopores (0.5-1.0 mm); many brown fresh fine roots; few spots of dark decomposed organic matter mixed in the soil matrix; clear and wavy boundary to the next horizon (AB).

AB (20/25-45/55 cm): Recognized by soil matrix colour and soil mottling pattern

Soil is black (5Y 2.5/1) in moist and gray (2.5Y 5/1) in dry conditions; soil texture is clay; 5-10% brownish orange (2.5YR 3/6) and brown (7.5YR 4/4) and distinct, clear fine mottles distributed mainly in the soil matrix; massive; sticky and plastic; ripe; few open biopores (<0.5 mm); few brown fresh roots and few, traces of decomposed organic matter; clear, wavy boundary with next horizon (Bg1).

Bg1 (45/55-70/75 cm): Distinguished by soil matrix color and soil structure

Gray (2.5Y 5/1) moist, light gray (2.5Y 7/1) dry; clayey texture; 15-20% strong brown (7.5YR 5/6) with distinct, clear fine mottles distributed mainly in the soil matrix; moderate, coarse subangular blocky; slightly sticky and plastic; ripe; common, open, fine, vertical channel biopores; very few, fine fresh roots; gradual, wavy boundary to Bg2 horizon.

Bg2 (70/75-130 cm): Justified by soil structure and mottling pattern

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

Cg (>130 cm): Recognized by soil matrix color and soil material

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

APPENDIX II

Table II.1 Texture of each master soil horizon of soil profile (Cai Lay)

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture (USDA)
Ap	0-20	1.8	31.5	66.7	Clay
AB	20-45	2.2	30.3	67.5	Clay
Bg1	45-70	1.5	34.0	64.5	Clay
Bg2	70-130	2.9	38.6	58.5	Clay
Cg	> 130	50.9	29.8	19.3	Sandy loam

Table II.2 Soil bulk density, particle density, soil porosity of each soil horizon in the soil profile

Soil depth (cm)	Soil horizon symbol	Soil bulk density (Mg/m^3)	Soil particle density (Mg/m^3)	Soil porosity (%)
0 - 20	Ap	0.98	2.50	60.85
20 - 45	AB	1.39	2.63	47.29
45 - 70	Bg1	1.30	2.66	51.38
70 - 130	Bg2	1.22	2.65	54.17

Table II.3 Hydraulic conductivity and permeability class of each soil horizon in the soil profile

Soil depth (cm)	Soil horizon symbol	K_{sat} values (m/s)	Permeability (O'Neal classification)
0 - 20	Ap	$3.4*10^{-5}$	Moderately rapid
20 - 45	AB	$1.1*10^{-7}$	Very slow
45 - 70	Bg1	$3.0*10^{-7}$	Very slow
70 - 130	Bg2	$5.2*10^{-7}$	Slow

Table II.4 Soil water content at field capacity and wilting point and available water content in the different master soil horizon

Horizon	Soil depth (cm)	Field capacity (m^3/m^3)	Wilting point (m^3/m^3)	Available soil water content (m^3/m^3)
Ap	0-20	0.507	0.199	0.175
AB	20-45	0.443	0.257	0.093
Bg1	45-70	0.459	0.251	0.093
Bg2	70-130	0.481	0.233	0.159

Table II.5 Analytical determinants of each master soil horizon of soil profile

Horizon	Depth	pH_{H2O}	EC	O.C	Total N	P_2O_5	Avail. P	CEC	Na	K	Ca	Mg
	(cm)		(dS/m)	(%)	(%)	(%)	(mg/kg)		(cmol (+)/kg soil)			
Ap	0-20	6.06	0.3	1.51	0.14	0.06	10.3	25.91	0.92	0.18	13.83	4.68
AB	20-45	6.26	0.3	0.98	0.10	0.03	1.6	27.98	1.08	0.16	14.16	5.69
Bg1	45-70	6.65	0.2	0.33	0.07	0.04	1.2	27.33	0.99	0.15	13.31	5.48
Bg2	70-130	7.20	0.3	0.19	0.06	0.05	1.3	25.52	1.25	0.19	12.42	5.37