Management practices and climate change influencing on rice yield and soil organic carbon in Northeast Thailand

(東北タイにおける管理作業と気候変動のイネ収量と土壌有機炭素への影響)

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Chapter 1

General introduction

1.1 Background

Climate change is an environmental concern worldwide and evidence is getting stronger that the global warming has been induced by the present human activities (IPCC, 2001). The major concerns that drive global climate changes include increasing concentrations of atmospheric carbon dioxide (CO_2) and other greenhouse gases (GHGs) (Abao et al., 2000; IPCC, 2001; Li et al., 2005). Climate change threats agricultural production through higher and more variable temperatures, changes in precipitation patterns and increased occurrences of extreme events as droughts and flood (Nelson et al., 2009). However, soil organic carbon (SOC) has been recognized as an important component in the global carbon (C) cycling, particularly in the context of the climatic change (Van Camp et al., 2004), because it can be a source of CO_2 and other GHGs or a sink by sequestering SOC. Thus, soil management methods which favor the maintenance of SOC, can be expected to influence the C storage pool (Lal et al., 1998), improving water capture and water use efficiency (Unger, 1990), nutrient cycling and retention, and GHG emissions (Doran and Parkin, 1994; Lal, 2003; Dou et al., 2008).

Rice cultivation usually depends on climate conditions, with both climate variability as well as climate change, which may affect rice yield (Easterling et al., 2007; Reidsma et al., 2010). Temperature, CO_2 concentration, rainfall and soil water availability can affect the processes related with the accumulation of dry matter such as leaf area expansion, respiration and photosynthesis, which can affect plant growth and crop yield (Olesen and Bindi, 2002). However, climate change impact may vary in different parts of the world, which depends on the climatic and soil conditions of each region. For example, Rosenzweig et al. (1993) predicted that crop production will decrease in the low-latitudes and increase in the mid-latitude and high-latitude regions. Bachelet and Gray (1993) reported that the rice yield will decrease by increasing the mean daily temperature in Asian countries and may enable to expand the rice growing areas in northern China and Japan. Matthews et al. (1997) indicated that declines in rice yield were predicted under the Goddard Institute of Space Studies (GISS) and the United Kingdom Meteorological Office (UKMO) General Circulation Models for Thailand, Bangladesh, southern China and western India, while increases were predicted for Indonesia, Malaysia, and Taiwan and some parts of India and China. Vaghefi et al. (2013) point out that rising temperature could reduce the rice production grievously in the rice growing areas of Peninsular Malaysia. Moreover, land management practices are also extremely important that can improve crop yield and resistance to climate change impacts (Smith et al., 2008). The long-term use of land for rice cultivation without improve soil quality, leading to the pertinent nutrient losses (e.g. nitrogen (N), phosphorus (P) and potassium (K)) through runoff and leaching with rainfall or irrigation exceeds and release to atmosphere as CO_2 (Havlin et at., 1999). Therefore, management practices that maintain soil C could be the most important way for restoring, maintaining, and improving soil quality. In doing so, the manure application or crop residues should be practiced where climate and water resources will support the implement (Karlen, 1993; Kaihura et al., 1999; Chivenge et al., 2007). The area of 35 million ha in Thailand have had a problem of soil and nutrient depletion (Ministry of Agriculture and Cooperatives (MAC) Thailand, 2015). As about 16 million ha of soil in Thailand contained organic matter (OM) lower than 1.5%, especially soil in Northeastern Thailand. As the majority of agricultural land in Thailand is used for rice cultivation (Land Development Department (LDD) Thailand, 2011), most of paddy field's soil in Thailand is assumed to have this problem. Apparently, rice straw burning is the most practice to eliminate for the next crop cultivation because of the ease and convenience of tillage to prepare for the next crop as well as releasing nutrients contained in the residue for the next crop (Gadde et al., 2009). Singh and

Singh (2001) also noted that burning causes a loss of nutrients and OM. There is not only the macro-nutrients contained in the rice straw, namely N, P and K, but the micro-nutrients also contained such as sulfur and silicon (Dobermann and Fairhurst, 2002). The continuous burning rice straw leads to reduce organic C (OC) and organic N, and soil aggregation (Malhi and Kutcher, 2007), water runoff, soil erosion (Biederbeck et al, 1980), and decreased the grain yields (Singh and Sidhu, 2014). The study by Dormaar et al. (1979) found that at long-term wheat growing areas, where straw is burnt showed a decrease in soil polysaccharides and in the percentage of water-stable aggregates, while NH_4-N and available P were increased. Farmers have tried to compensate the nutrient depletion in soil by overusing chemical fertilizers in order to improve the yield of rice production. Therefore, mismanagement practices and climate change impacts are the issues being urgently investigated for sustaining land management practices.

However, various strategies of land management are currently being developed to improve rice productivity as well as SOC sequestration, for example, water management (Tian et al., 2013), cultivation methods (Xu et al., 2011), fertilization management (Srinivasarao et al., 2012), rice straw (Liu et al., 2014), manure (Zhao et al., 2013). In addition, climate change and rising atmospheric CO_2 might also effect on rice yield (Parry et al., 2004) and SOC (Lal, 2004a). Even the soils have the potential to mitigate increasing CO_2 concentrations through C sequestration, land misuse and soil mismanagement have caused depletion of SOC (Li and Zhang, 2007; Pan et al., 2009; Bhattacharyya et al., 2010; Li et al., 2010). In order to estimate these effects in rice fields, the concept of net global warming potential (GWP) was proposed based on the radiative properties of CO_2, methane (CH_4) and nitrous oxides (N_2O) emissions and SOC variations, expressed as kg CO_2eq ha^{-1} yr^{-1} (Robertson and Grace, 2004). The agricultural practices can be related to GWP by estimating net GWP per ton of crop yield, which is referred to as greenhouse gas intensity (GHGI) (Mosier et al., 2006). Moreover, computer simulation models of the soil, crop yield, and atmosphere system can make a valuable contribution to determine crop responses and predicting crop performance, and environmental impacts for different management practices. Environmental Policy Integrated Climate (EPIC) model is a comprehensive agro-ecosystem model capable of simulating the growth of crops grown in complex rotations and management operations and can be used to simulate crop yield and SOC under diverse regional environment conditions, climate conditions, and management practices (Easterling et al., 1996, Adejuwon, 2005; 2006, Williams, 1995; Williams et al., 2006, Priya and Shibasaki, 2001, Tan and Shibasaki, 2003, Thomson et al., 2006, Wang and Li, 2010, Balkovič et al., 2011), which cover the basic output studied for this thesis research. There are no studies which have evaluated the ability of EPIC0509 to simulate field-scale variability of SOC, and no calibration and validation studies of EPIC0509 has been performed in Northeast Thailand. However, the previous studies (Xiong et al., 2008; Niu et al., 2009; Xiong et al., 2014) have conducted at large scales (basin, country or regional), which did not incorporate local heterogeneity such as local climate, soil properties, farmer management practices. Climate change impacts at different scales may influence at different severity. Local scale simulation is usually difficult because the precise data is rarely accessible and available. Therefore, there is a pressing need to improve the accuracy of the EPIC model simulation through the use of local specific data for model calibration and validation procedures. Our knowledge can contribute to understanding the consequences of long-term climate change, which is important for the agricultural policies and the choice of mitigation strategies.

1.2 Research Objective

The goal of this study is to examine the influences of land management practices, and climate change attributes on rice yield and SOC in Northeast Thailand. To achieve this goal, we performed three specific objectives as following details:

1) To investigate the distribution of rice yield and SOC content under different land management practices, and analyzes the relationship between rice yield and SOC with pertinent management practices (manure and fertilizer applications).

2) To estimate the effect of land management practices on net GWP and GHGI.

3) To evaluate the reliability of EPIC model calibration and validation processes based on local scale data, and evaluate the possible impact of climate change on rice yield and SOC sequestration.

1.3 Structure of dissertation

The present dissertation entitled "Management practices and climate change influencing on rice yield and SOC in Northeast Thailand" concerns with the investigation of farmers' actual management practices and assessment of climate change impacts on rice yield and SOC. There are seven chapters in this dissertation. General introduction and objectives are mentioned in chapter one. The second chapter discusses the literature reviews and relevance of the study. The practices sustaining soil organic matter and rice yield under different land management practices are detailed in the third chapter. The fourth chapter provides the result of the effects of land management practices on GWP and GHGI from rice production. Using EPIC model to predict local scale impact of climate change on rice yield and soil organic carbon sequestration in tropical monsoon area is presented in the fifth chapter. Chapter sixth is for general discussion. Finally, the dissertation conclusion and recommendations are provided in the last chapter.

Chapter 2

Literature review

Greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxides (N_2O) and chlorofluorocarbons (CFCs) were absorbed the thermal radiation by the earth‘s surface which, could lead to the changing of climate. Among these GHGs, CO_2 is a major cause and responsible for more than half the radiative forces rerated with the global climate change (Watson et al., 2000). According to IPCC (2001), the average surface temperature is forecasted to increase by 1.4 °C to 5.8 °C in the year 2100.

2.1 Climate change and global warming

2.1.1 Climate variability

Climate variability is temporal variations in the mean condition of the climate parameters. Such variability can be attributed to intrinsic properties of the system itself or external factors. However, changes in climate variability and severe climate events have recently caught more and more attention (IPCC, 2001). Climate variability and occurrences of severe climate events have become a major concern, particularly in Asia where agricultural sector has suffered consequences of severe climate events such as droughts and floods, as well as annual rises of temperature that results in substantial economic loss (Shukla et al., 2003). According to the IPCC report (AR4) on the climate trend across seven sub-regions in Asia, surface temperature conditionings are more pronounced during winter than summer. In North Asia, the range of temperature increase is less than +1 ^{o}C and up to +3 ^{o}C per 100 years. Apart from the growing number of rainy days and the greater amount of annual precipitation, the longer heat waves have widely occurred in Asia as well, causing disasters such as floods, landslides, and mud flows (IPCC, 2007).

2.1.2 Climate change scenarios

Climate change scenarios are based on different models and assumptions, which leads to different estimations of temperature and precipitation changes. In estimating the impact of climate change in the future, we need to understand the concept of atmospheric GHG concentrations to which climates are sensitive. According to IPCC Special Report on Emission Scenarios (SRES), there are four storylines: A1, A2, B1 and B2, each of which is characterized by its own set of values representing different developments in social, economic, environmental, technological and demographic dimensions. A key source of input to the climate model developed to predict future climate change is concentration scenarios simulated based on emission scenarios (IPCC, 2007). Table 2-1 outlines the four storylines by their economic-environmental priorities and global-regional development. The global projections in temperature change, atmospheric CO_2 concentration and sea level rise were given in Table 2-2.

Table 2-1 The characteristics of the SRES storylines (adapted from IPCC, 2007; Akarsh, 2013)

	ECONOMIC		
GLOBAL	**A1 storyline** **World**: market oriented **Economy**: fast per capita growth **Population**: 2050 peak, then decline **Governance**: strong regional interaction; income convergence **Technology**: three scenario groups: A1F1: fossil intensive A1T: non-fossil energy sources A1B: balance across all sources.	**A2 storyline** **World**: differentiated **Economy**: regional oriented; lowest per capital growth **Population**: continuously increasing **Governance**: self-reliance with preservation of local identities **Technology**: slowest and most fragmented development	**REGIONAL**
	B1 storyline **World**: convergent **Economy**: service and information base; lower growth than A1 **Population**: 2050 peak, then decline	**B2 storyline** **World**: local solutions **Economy**: intermediate growth **Population**: continuously increasing at lower rate than A2	

	Governance: global solutions to economic, social and environmental sustainability **Technology**: clean and resource efficient	**Governance**: local and regional solutions to environmental protection and social equity **Technology**: more rapid than A2; less rapid, more diverse than A1/B1	
	ENVIRONMENTAL		

Table 2-2 Global projections in temperature change, atmospheric CO_2 concentration and sea level rise (Akarsh, 2013)

Scenario	Temperature change[(a)] (°C)	Atmospheric CO_2 concentration[(b)] (ppmv)			Sea Level Rise[(c)] (cm)
		1990s	2020s	2050s	
A1F1	2.4-6.4	358	432	590	26-59
A1T	1.4-3.8	-	-	-	20-45
A1B	1.7-4.4	-	-	-	21-48
A2	2.0-5.4	358	432	549	23-51
B1	1.1-2.9	358	421	492	18-38
B2	1.4-3.8	358	422	488	20-43

(a) and (c) (IPCC, 2007), (b) (Arnell et al., 2004)

2.2 Soil organic carbon

Soil organic carbon (SOC) is a rich source of C in the biosphere. As a measure of soil organic matter (SOM), SOC is produced by a variety of sources ranging the leaf litter, branches or roots of plants, and manure, to the small proportion of living microbial organisms (Kögel-Knabner, 2002). These organisms' activities – particularly the decomposition of plant residues –result in C being brought deeper down into the soil profile. Normally, C is returned to the atmosphere as CO_2 when the majority of organic matter (OM) goes through rapid decomposition in upper soil layers (Nowak et al., 2015). This process in which microbial organisms, roots, and soil fauna contribute to the release of C back to the atmosphere is called soil respiration, which is a vital part of the soil C cycle (Classen et al., 2015).

The OM that remains from early decomposition slowly goes through a process called humification which finally turns it into a set of humic substances with chemical stability and resistance to any subsequent breakdown (Lehmann and Kleber, 2015). However, it should be noted that only a small part of the C input will eventually turn into humus, and as this process usually takes thousands of years to complete (Parton et al., 1993). As processed SOM and organic material are different in mean residence time, they become parts of different pools. Organic materials, including plant residues and rapidly decomposing debris, with a mean residence time of years to decades belong to the labile C pool while, in contrast, processed SOM with a much longer mean residence time of hundreds to thousands of years belongs to the long-term storage called recalcitrant C pool (Knicker and Hatcher, 1997; Jastrow et al., 2007). It is estimated that, as for the long-term pool, the rate of humification ranges from 0.2 to 12 g C m^{-2} per year (in ecosystem types: Tundra, Boreal forest, Temperate forest, Tropical forest, Temperate grassland, and Temperate desert) and the rate of C accumulation stands at ~0.4×10^{15} g C yr^{-1} (Schlesinger, 1990).

SOC usually makes a substantial part of the total soil mass, with an exception of agricultural soils that usually has less than 5% SOC. Its proportion decreases as the soil depth increases. According to Capon et al. (2010), the amount of SOC, as a total measure over soil depths, is reportedly estimated from about 10 t C ha^{-1} to about 160 t C ha^{-1} in the top 30 cm of soil in undisturbed lands (Valzano et al., 2005; Roxburgh et al., 2006; Wynn et al., 2006) and sometimes up to 250 t C ha^{-1} in the case of rich soil in undisturbed lands (Webb, 2002). As it has been estimated, globally there are about 1400 Gt of SOC, about double the quantity of CO_2 in the atmosphere (Falloon et al., 2006; Lal, 2007). As a major determinant of soil biological activity, SOM can help shape both soil chemical and physical properties to a significant extent (Robert, 2001). As the SOM increases, soil structure aggregation and stability, infiltration rate, resistance to erosion as well as water retention, will improve (Bot and Benites, 2005). The amount of SOM is partly dependent on geographical variations. Such processes may also include inputs from plant residues, nutrient flows, as well as fauna, and factors that play a part in determining the amount of SOM include its accumulation and the decomposition rate.

2.3 Sustainable management practice

Agriculture is part of the solution and opportunity to reduce emissions through C sequestration, soil and land use management, and biomass production. Climate change becomes threats to agricultural production as temperatures get higher and more varied, precipitation patterns alter and severe disasters such as droughts and floods become more frequent (Baharuddin, 2007; Nelson and Thompson, 2009). Soil fertility management is an agricultural practice adapted to maximize efficiency of nutrient and water use and to reach enhanced agricultural productivity (Bationo, et al., 1998; Vanlauwe et al., 2015). Several management strategies suggest the combined use of mineral fertilizers, locally available soil amendments and OM to replenish lost soil nutrients. These practices, as a result, can improve the soil health through integrated management of soil fertility, which can be implemented through the combined use of fertilizer and organic inputs, together with appropriate techniques (Bogota, 1985; Olk et al., 1999; Lee, 2005; Vanlauwe, 2009).

2.3.1 Effects of chemical fertilizer and manure application on soil properties, crop yields and SOC

Several studies pointed out that when nitrogen (N), phosphorus (P) and potassium (K) fertilizer was used together with inorganic fertilizer, the crop yield and soil fertility significantly increased (Subbiah and Kumaraswamy, 2000; Dixit and Gupta, 2000; Babu et al., 2001). Verma and Sharma (2008) reported that the long term use of chemical fertilizer alone deteriorated whereas the application of N, P and K at recommended rates and organic amendment improved soil physical properties over control of no fertilizer application. Singh et al. (2001), Silva et al. (2005) and Khan et al. (2007) observed that the combined application of N, P and K and organic manures significantly increased the straw yields of rice crop. The results also noted that organic manures especially green manure and farm yard manure led to an increase in both rice and wheat yields. The addition of organic amendments into the soil can increase OM content, CEC, total N, exchangeable K, available P and S and improved soil structure and increased rice yield (Zaman et al., 2000; Shukla et al., 1998; Swarup and Singh, 1994). In addition, Dou et al. (1994) concluded that the application of pig manure, rice straw and chemical N fertilizer increased soil porosity, microstructural coefficient, reactivities of organic C and N contents of the paddy soil. Maeda and Hirai (2002) conducted a field experiment with rice from 1991 to 2000 in Japan and found that continuous application of farmyard manure increased the pH, available P content, and the uptake of P and K by the plants.

2.3.2 Effects of rice straw on soil properties, crop yields and SOC

Removing crop residue from the field or on-field burning may leave some negative impact on the crop, soil and air. Rice straw is among the organic materials that have the potential to be recycled to restore SOM and improve soil properties. Several studies reported that conventional agriculture has preferred leaving the entire crop residue in the soil without tillage (Smith et al., 1998; West and Post, 2002). The lack of rice residues in soils can cause extremely low SOM and brings negative effects to soil health as it immobilizes soil N and inhibits the plant growth (Williams et al., 1968; Yoneyama and Yoshida (1976a; b); Rao and Mikkelsen, 1976; Nagarajah et al., 1989; Trinsoutrot et al., 2000).

SOC is the most indicative factor of soil C sinks. The amount of SOC could be enlarged through the application of organic fertilizers from composting along with GHGs mitigation (Rice and Reed, 2007; Kane, 2015; Yang et al., 2015). Reportedly, the use of such fertilizers leads to enhanced soil quality as SOM is improved and agricultural sustainability is promoted (Liu et al. 2006). On the other hand, it has been reported that a decrease in either SOM or SOC concentrations will result in lower productivity as the soil health declines and nutrient cycling mechanisms are interrupted (Farquharson et al., 2003; Loveland and Webb, 2003). It has also been found that constant use of chemical fertilizers and/or monoculture of crops may result in a small amount of additional SOC (Gregorich et al. 2001; Sarno et al. 2004), while SOM can be enhanced over time through continuous use of organic additions as it brings C fractions to the soil (Blair and Crocker, 2000; Witt et al. 2000). In the long run, the combined application of organic manures together with NPK fertilizers will lead to a remarkable increase of SOC as well as soil N (Reddy et al. 2003). Hence, one of the most efficient ways to revive agricultural soils is to put crop residues back as composting, which primarily brings nutrients back to the soils along with other benefits.

2.4 Influences of climate variability on rice growth and yield

2.4.1 The role of climate for rice growth and yield

In general, as plant characteristics are often adapted to the climatic conditions of plants' growing areas, climatic and weather conditions are the deciding factors for yield formation and plant growth. Climate, as a result, is the primary indicator of what plants could be grown in a specific area as it determines temperatures during days and nights, as well as the amount of precipitation and how it is distributed seasonally. Thus, the period of growing season is based on the evapotranspiration and amount of rainfall, which are included ground water availability, and the shortage and distribution of soil water (Jin et al., 1999; Wild, 2003). Climate imposes direct influences on the physiological processes of plant growth and development. Furthermore, climate also defines crop pests, diseases, and grain yields, thereby becoming one of the most important issues to be concerned when it comes to food security (Ziska et al., 2011; Lobell and Gourdji, 2012). To understand climate variability needs to understand the main factors of climate such as rainfall, solar radiation, temperature and relative humidity. A major concern of the world, thus, mainly involves climate variability and occurrences of severe disasters. Following is a strong need to quantify the growth and yield responses of important crops and to identify suitable land use options to sustain agricultural productivity under such a vast range of climate variations (Shukla et al., 2003; FAO, 2008). Rice yields can be directly affected by climate change as temperatures and the amount of CO_2 change. In addition, indirect effects can be imposed by other factors such as irrigation water accessibility, pests and diseases, soil fertility and erosion (Sinha and Swaminathan, 1991; Khan et al. 2009).

2.4.2 Climate change scenarios and their impact on rice growth and yield

Climate change has become a key concern due to the challenges it poses on rice production such as water shortage and other factors that limit growing capacity (Kang et al., 2009; Karn, 2014; Mancosu et al., 2015). Various crop models and climate change scenarios are taken into account in Asia to evaluate the impact of climate change on rice production (Ainsworth and Long, 2005; Lee et al., 2012; Kim et al., 2013). The SRESs cover a wide range of CO_2, other greenhouse gases, and sulfur emissions. It is predicted that, based on various GCMs, the rise of global mean temperatures over the period from 1900 to 2100 will range from 1.4 to 5.8 ^{o}C while larger uncertainties have been observed by the models that examined climate changes at regional levels. As a result, future research related to global climate change must be able to handle the uncertainties from various sources such as GCMs, emission scenarios, and impact models (Torvanger et al., 2001; Pittock et al., 2001; Challinor et al., 2005; IPCC-TGICA, 2007; Giorgi, 2010).

Based on four scenarios prediction, temperatures in the 21st century are projected to increase due to a continuous rise of CO_2 emissions. The projections highlight the fact that natural physical and biological systems, such as plant and hydrology, are responsive to the increasing CO_2 emissions (IPCC, 2007). For example, warmer temperatures are associated with the elevated CO_2 increases in sea surface temperatures, resulting in more frequent rainfall and more water available for plants. Meanwhile, plants alter their responsive functions due to elevated CO_2 concentrations. Plants could gain either an advantage or disadvantage from such changes in climate conditions. Air temperature and precipitation are considered two major climatic variables that are important factors controlling for all crop production. Adejuwon (2006), Kang et al. (2009) and Ray et al. (2015) dedicated their works on the interaction of individual climatic variables on crop productivity. The findings suggest that higher temperature and fluctuated rainfall can generally decrease and increase crop yields. In addition to the effect of changes in temperature and precipitation on plant, the rising atmospheric CO_2 concentration is also a factor that directly affects crop development and productivity. According to Erda et al. (2005) and Attavanich and McCarl (2011), the rising CO_2 fertilization effect associated with higher temperature is known to stimulate photosynthetic systems. Therefore, under optimum climate conditions crops including rice, wheat, and sorghum gain benefit from the CO_2 fertilization effect (Richards, 2000; Parry et al. 2004; Erda et al., 2005; Motha and Baier, 2005; McGrath and Lobell, 2013; Degener, 2015; Grossi et al. 2015).

2.5 Influences of climate change on SOC

There is a direct relationship between global warming and the functioning of the global C cycle because increases in concentrations of atmospheric CO_2 and CH_4 are related to global warming through the anthropogenic enhancement of the greenhouse effect (Hermle et al., 2008). To put it simply, the decomposition of SOM is more responsive to temperature change than to NPP (Wamelink et al., 2009). Therefore, rising temperatures tend to result in a net release of C from soil to the atmosphere since SOM decomposition has been more affected than NPP. This is likely to result in a positive feedback mechanism in which the transfer of soil C elevates atmospheric CO_2 concentrations that, in turn, can result in increased surface temperatures and thus in more loss of soil C through increased decomposition rates (Cox et al., 2000). This positive feedback, however, may also have a potential inhibitor. Greater soil N availability may be stimulated by the accelerated decomposition, resulting in higher NPP. This may lead to a potential rise in C inputs into the soil as a result of litter fall and rhizodeposition, which can, in turn, rather counterbalance the elevated loss of soil C (Bhattacharya et al., 2000; Davidson and Janssens, 2006).

The soil C can significantly be affected by climate change due to the fact that variations in temperature, rainfall and CO_2 concentration can impose some influence on the transformations of soil C stocks, the soil C decomposition, and the C inputs to soil (Melillo et al., 2002; Jones et al., 2005; Farage et al., 2007). Many researchers share the same vision that global warming can result in a rise of soil respiration, leading to increasing CO_2 release that can aggravate the global warming (Hermle et al., 2008). Nevertheless, at the moment, researchers cannot reach an agreement on issues such as how climate change affects soil C dynamics and what feedbacks are given back to the climate. For example, it is reported that the soil C sequestration rate and the soil C content are likely to expand as the temperature and precipitation increase (Knorr et al., 2005; Thomson et al., 2006). Research findings have also shown that at higher temperature and precipitation the organic material decomposition and the losses from soil have risen (Curtin et al., 2011). Alvarez and Alvarez (2001) and Grace et al. (2006) found that the SOC diminishes as temperature and precipitation rise. In contrast, Andersson and Nilsson (2001) concluded that at higher temperature and precipitation, the cumulative dissolved organic C (DOC) in the humus layer is likely to rise as well. Meanwhile, temperature is considered as a primary factor on DOC leaching (Solomon et al., 2009), whereas Cox et al. (2011) reported that in their study temperature did not affect the DOC production. In a meta-study conducted by Rustad et al. (2001), a wide range of studies on experimental ecosystem warming and gradient were examined, revealing that the net N mineralization rate and the nitrification rate of the upper organic soil horizon contributed significantly to the increased warming.

As it has been hypothesized, global warming may cause a drop of soil C in the short run, but in the long run, such soil C losses can potentially be compensated by the rise in C input to the soil and through the chemical and physical reactions that can lead to the stabilization of soil C (Vleeshouwers and Verhagen, 2002). Reportedly, future climate warming and drying as a result of a decrease in rainfall and heat stress on crops will lead to a reduction in the productivity and organic C inputs, while higher temperatures will accelerate the SOC decomposition (Johnston et al., 2009).

It has been suggested that in the next 50 years higher temperatures and CO_2 can cause the saturation response in the terrestrial sinks, which according to researchers means a faster accumulation of atmospheric CO_2 than it is now (Canadell et al., 2007). A warmer and drier climate will also make the SOC environmental equilibrium decline (Uvarov et al., 2006). Particularly in areas with lower rainfall levels, it is anticipated that a drier climate will affect heavier soil types more than other types, followed by years of poorer production and a fall in the plant residue C inputs (Vleeshouwers and Verhagen, 2002).

In temperate regions, the SOC pool is high, in contrast to dry regions. The concentration reaches its maximum level in organic or peat soils where is it extremely high. The SOC concentration can vary greatly from one ecoregion to another and has been observed to be lower in warm and dry than in cool and moist regions. Thus, the total soil C concentration is four times the biotic concentration and approximately three times the atmospheric pool (IPCC, 2001; 2007). Precipitation also plays a vital part in determining the amount of OM in soil. Every change in rainfall regimes can potentially influence the SOC storage, and such changes are, for example, shifts in rainfall timing and variability, as well as intensity (Zhang, 2005; IPCC, 2007).

Soils in ecosystems with higher levels of precipitation are capable of storing higher levels of C (Jones et al., 2005). An increase in mean annual rainfall can influence the soil properties and soil degradation (Davidson and Janssens, 2006; Johnston et al., 2009). For example, in desert ecosystems, processes that control SOC are highly dependent on the seasonal availability of soil moisture and clearly sensitive to rainfall. Cold deserts, in particular, receive low levels of rainfall and snow falling predominantly during the winter and early spring when soils are cold. This seasonal climate regime results in low rates of C-cycling in winter and high rates of cycling in spring before soils become too dry in the summer (Jones et al., 2005; Aanderud et al., 2010).

Factors such as latitude, altitude, aspect and other environmental factors can affect the quantity of OM in soils due to the relationship between temperature and these factors (Jansson et al., 2008; Solomon et al., 2009). As latitude decreases, which means as one moves away from the equator, soils usually store more C due to the fact that dead plants decay at a lower rate in colder areas. Due to climate change, when high-latitude soils become warmer and wet soils become drier, these soils will likely release more CO_2 to the atmosphere that, in turn, leads to a large positive feedback to the initial warming. Such a process must be in progress at the moment in the peatlands of the North Pole. It has been estimated that as temperatures increase, 11 to 34 Gt of C per degree of warming globally will be lost from soils. The response is expected to be only 5 to 17 Gt since an increase in temperatures usually accelerates the decomposition process, which, in turn, releases nutrients necessary for plant growth. A rise in plant growth will consequently raise C storage in the soil (Lugato and Berti, 2008).

2.6 EPIC model description

Developed in the early 1980s, the EPIC model was to measure the impact of erosion on agricultural productivity (Williams et al., 1984). Originally, EPIC stood for the Erosion Productivity Impact Calculator, as it was initially designed to estimate erosion impacts on crop productivity (Williams, 1990). Evolution of the model, with incorporation of functions to simulate environmental processes related to water quality and SOC sequestration, merited its name change to the Environmental Policy Integrated Climate model. Prior to the modification to add the ability to make integrated environmental impact assessments, the model was originally developed to measure effects of erosion on crop biomass and soils (Putnam et al., 1988). The modified model is now capable of assessing environmental factors in agriculture (Williams, 1995) and simulating a variety of crops and tillage operations, as well N, P, and C cycling (Izaurralde et al., 2001; 2006), hydrological balances, wind and water erosion or leaching, and soil density changes. The modification also enabled the model to measure what effects that are caused by the changes in CO_2 are imposed on the plant growth (Stockle et al., 1992) and to simulate the biophysical impacts on agro-ecosystem functions (Brown and Rosenberg 1999). The EPIC model processes include weather, hydrology, erosion, nutrient cycling, C cycling, pesticide fate, soil temperatures, crop growth and tillage/management operations (Rinaldi, 2001) as shown in Figure 2-1. EPIC model has been used in experimental applications and was calibrated and validated for several field crops and has been used to investigate long-term consequences of climate change coupled model and future climate scenarios (Tubiello et al., 2000).

The EPIC model version EPIC0509 and interface (i_EPIC) has been used in this study analysis. An interface called i_EPIC is used to manage the multiple EPIC runs which are necessary for calibration. i_EPIC was developed and is maintained by Iowa State University. In order to increase the transparency of input, i_EPIC uses Microsoft Access databases as its input files rather than the more cryptic text-based input files used directly by EPIC. When input modifications are required, these databases can easily be opened and edited, then reloaded into i_EPIC. i_EPIC generates the text-based input files required by EPIC, and then translates EPIC's output into preformatted output tables in the same Microsoft Access database (Johansson et al., 2007). More information on EPIC can be finding at http://epicapex.brc.tamus.edu. The current EPIC community code can be downloaded from http://www.public.iastate. edu/~tdc/i_epic_main.html.

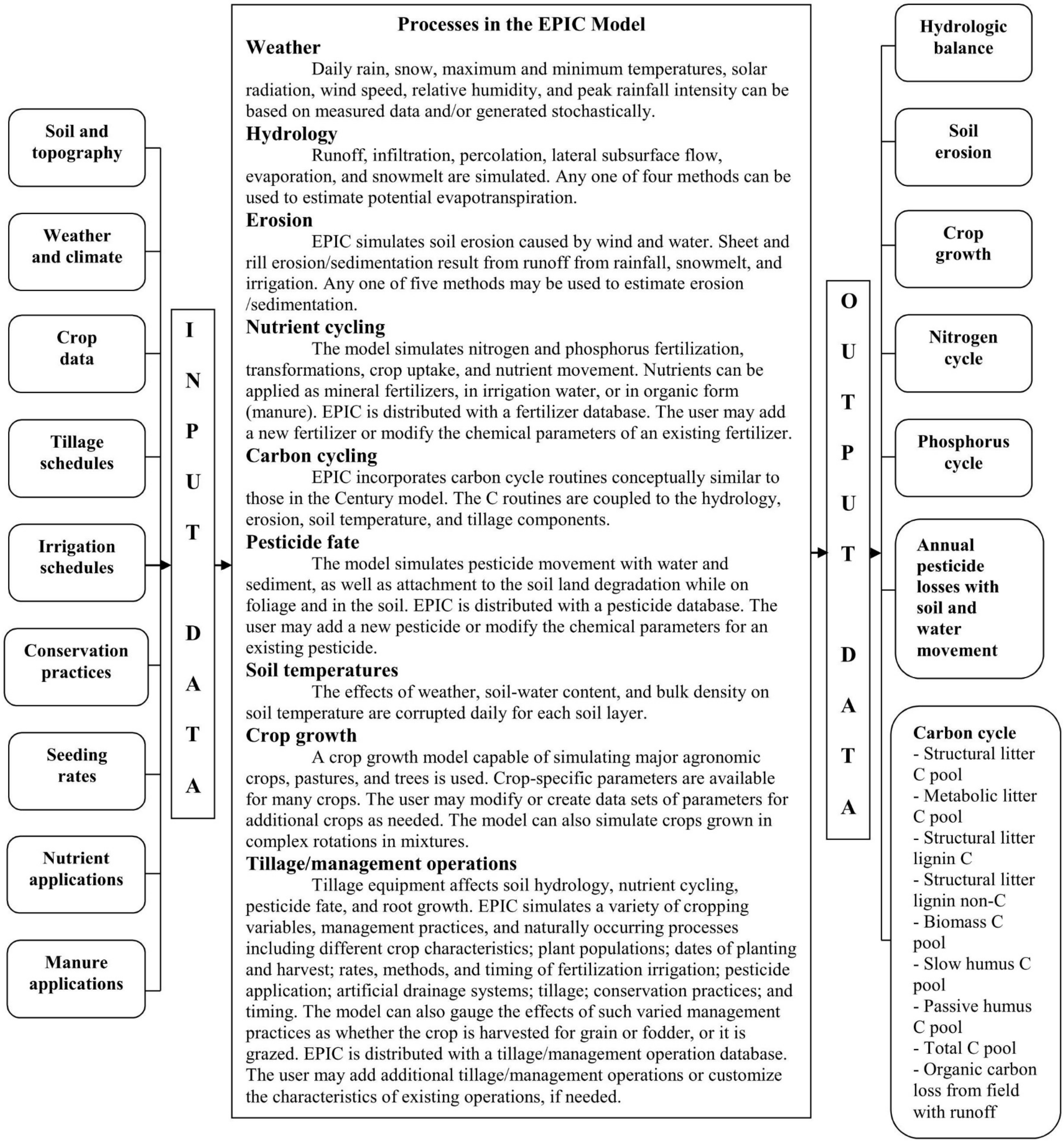


Figure 2-1 General schematic of the key processing steps required of the i-EPIC model

Source: modified from USDA (2006)

2.6.1 Crop growth model

EPIC model can simulate growth of both annual and perennial crops based on a single crop growth model. As for annual crop growth, the observation starts from the planting date until harvest date or until the accumulated heat unit reaches the predetermined potential heat unit. The model takes into account both crop growth constrains and stress factors, which undermine the plant growth, with the stress factor value ranging from 0 to 1 and records being made on temperature, amount of water, nutrient and aeration stresses for further adjustment of biomass accumulation (Sharpley and Wiliams, 1990).

The phonological development of the crop is based on daily heat unit accumulation and a Heat Unit Index value (HUI) is computed from 0 at planting to 1 at maturity (Sharpley and Wiliams, 1990).

$$HU_k = \frac{T_{mx,k} + T_{mn,k}}{2} - T_{b,j} \quad ; \quad HU_k \geq 0 \qquad (1)$$

$$HUI_i = \frac{\sum_{k=1}^{i} HU_k}{PHU_j} \qquad (2)$$

where HU, T_{mx} and T_{mn} are the values of heat unit, maximum temperature and minimum temperature in °C on day k. T_b and PHU are base temperature and Potential heat units require for crop j.

Crop yield is calculated as the amount of crop removed from the field and simulated as a function of above ground biomass accumulates at the end of crop growth and harvest index (Sharpley and Wiliams, 1990).

$$YLD_j = \left(HIA_j\right) \times (B_{AG})_j \qquad (3)$$

where HIA_j is the harvest index and B_{AG} is the above ground biomass in t ha^{-1} for crop j.

The potential daily increase in biomass is estimated as follows (Sharpley and Wiliams, 1990),

$$\Delta B_{p,j} = 0.001 \times (BE)_j \times (PAR)_j \qquad (4)$$

where $\Delta B_{p,j}$ is the daily potential increase in biomass in t ha^{-1} for crop j, $(BE)_j$ is the crop parameter for converting energy to biomass in kg ha^{-1} MJ^{-1} m^{-2} and $(PAR)_j$ is the intercepted photosynthetic active radiation in MJ m^{-2} derived using Beer's law equation. In order to incorporate the effect changing atmospheric CO_2 and vapor pressure deficit, *BE* value is adjusted as follows (Sharpley and Wiliams, 1990).

$$BE^* = \frac{(100 \times CO_2)}{(CO_2 + \exp(bc_1 - bc_2(CO_2))} \tag{5}$$

$$BE = BE^* - bc_3 \times (VPD - 1) \qquad VPD > 0.5 \tag{6}$$

where CO_2 is the atmospheric CO_2 level in ppm, VPD is the vapor pressure deficit in kPa and bc_1, bc_2 and bc_3 are the crop specific parameters.

$$PAR_i = 0.5 \times (RA)_i \times [1 - \exp(-0.65 \times LAI_i)] \tag{7}$$

where $(RA)_i$ is the solar radiation in MJ m^{-2} and LAI_i is the leaf area index in ith day of the year. The constant 0.65 is the extinction coefficient.

$$LAI_i = LAI_{i-1} + \Delta LAI \tag{8}$$

$$\Delta LAI = (\Delta HUF) \times LAI_{mx} \times [1 - exp((5 \times (LAI_{i-1} - LAI_{mx}))] \tag{9}$$

$$HUF_i = \frac{HUI_i}{HUI_i + exp[ah_{i,1} - (ah_{i,2}) \times (HUI_i)} \tag{10}$$

where *HUF* is the heat unit factor, $ah_{j,1}$ and $ah_{j,2}$ are parameters of crop *j*. Subscript *mx* is the maximum value, and Δ is the daily change.

For stressed conditions, harvest index is a function of heat unit index and water stress (Williams, 1995; Yin et al., 2014):

$$HIA = (HIA_i - HIA_0)\left(\frac{WS_i}{WS_i + exp(6.13 - 0.0883 WS_i)}\right) + HIA_0 \tag{11}$$

$$WS_i = \frac{\sum_{l=1}^{M} u_{i,\ l}}{E_{Pi}} \tag{12}$$

where HIA_i is the harvest index adjusted by heat unit factor on day *i*, HIA_0 is the minimum harvest index, WS_i is the water stress factor on day *i*, $u_{i,\ l}$ is the water use in layer *l*, and E_{Pi} is the potential plant water evaporation rate on day *i*.

$$HIA_i = HI_j \left(\frac{HUI_i}{HUI_i + exp(11.1 - 10HUI_i)}\right) \tag{13}$$

where HI_j is the potential harvest index for crop *j*, and HUI_i is the heat unit index on day *i*.

There are five environmental stresses (water, temperature, nutrients (N and P) and aeration) in EPIC model. The estimates (stress factors) range from 0.0 (the most severe) to 1.0, and the stresses affect plants in several ways (Williams, 1995; Easterling et al., 1998; Liu et al., 2014).

Water Stress: The water stress factor is computed by considering supply and demand in the equation:

$$WS_i = \frac{\sum_{l=1}^{M} u_{i,\ l}}{E_{Pi}} \tag{14}$$

$$E_P = \frac{E_0 LAI}{3},\ \ 0 \le LAI \le 3.0 \tag{15}$$

$$E_P = E_0,\ \ LAI > 3.0 \tag{16}$$

where WS_i is the water stress factor, $u_{i,\ l}$ is the water use in layer *l*, and E_{Pi} is the potential plant water evaporation rate on day *i*, E_p is computed from E_0 and LAI. E_0 is the potential evaporation, and *LAI* is the leaf area index.

Temperature Stress: The plant temperature stress factor is estimated with the equation:

$$TS_i = sin\left(\frac{\pi}{2}\ \left(\frac{T_G - T_{bj}}{T_{oj} - T_{bj}}\right)\right) \tag{17}$$

where *TS* is the plant temperature stress factor, T_G is the soil surface temperature (°C), T_b is the base temperature for crop *j*, and T_o is the optimal temperature for crop *j*.

Nutrient Stress: The N and P stress factors are based on the ratio of accumulated plant N and P to the optimal values. The stress factors vary nonlinearly from 1.0 at optimal N and P levels to 0. For N, the scaling equation is

$$NS_{S,i} = 2\left(1 - \frac{\sum_{k=1}^{i} UN_k}{(c_{NB})_i\,(B)_i}\right) \tag{18}$$

where NS_S is a scaling factor for the N stress factor, UN is the crop N uptake rate on day k (kg $ha^{-1}d^{-1}$), c_{NB} is the optimal N concentration of the crop on day i, and B is the accumulated biomass (t ha^{-1}).

The N stress factor is computed with the equation:

$$NS_i = 1 - \frac{NS_{S,i}}{NS_{S,i} + exp(3.39 - 10.93 \times NS_{S,i})} \tag{19}$$

where NS is the N stress factor for day i. The P stress factor, PS, is computed with above equations written in P terms.

Aeration Stress: When soil water content approaches saturation, plants may suffer from aeration stress. The water content of the top 1 m of soil is considered in estimating the degree of stress:

$$SAT = \frac{SW1}{PO1} - CAF_j \tag{20}$$

$$AS_i = 1 - \frac{SAT}{SAT + exp(-1.291 - 56.1 \times SAT)},\ \ SAT > 0 \tag{21}$$

where SAT is the saturation factor, SW_l is the water content of the top 1 m of soil (mm), PO_l is the porosity of the top 1 m of soil (mm), CAF is the critical aeration factor for crop j (~0.85 for many crops), and AS is the aeration stress factor.

2.6.2 Carbon flows in EPIC model

SOC is further grouped into various pools with unique characteristics and decomposition rates following first-order kinetics, followed by the transfer of C from animal manures and crop residues into different pools with varied levels of stability. The advantage of the models whose structures are multi-compartmental lies with the fact that they provide flexibility and the ability to accommodate control variables. Below is the fundamental equation of C flux between pools (Polyakov and Lal, 2004):

$$\frac{\partial C}{\partial t} = -kmpC_{soil} + h \qquad (22)$$

where C_{soil} is the concentration of organic C in soil; t is the time; k is the first-order decomposition coefficient; m and p are the correction factors for soil temperature and moisture, respectively, h is the additional rate (independent of decomposition rate), such as erosion, deposition or net primary production.

The Century model (Parton et al., 1987; 1994) is capable of simulating SOM across a wide range of climatic conditions and land usages (Kelly et al., 1997). In the model, SOC is classified into three pools based on the mineralization and turnover rates. Accounting for around 5-15% of the total SOC, the first is labile pool which represents microbial and fungal biomass, and compounds that can easily break down into minerals, with a turnover rate of months to years. Accounting for 20-40% of the total SOC, the second is a slower pool with a turnover rate of several decades, representing recently added residues. Accounting for the remaining 60-70% of the total SOC, the third pool is a stable or long-term storage with a turnover rate of hundreds to thousands of years.

EPIC simulates dynamic C processes using C routines conceptually similar to those in the Century model (Izaurralde et al., 2001; 2006). Carbon processes are coupled to the hydrology, erosion, soil temperature, plant growth, nutrient cycling, and tillage components. In Figure 2-2, we can see that plants gather and package energy from the sun through photosynthesis, the process in which light energy is trapped and turned into chemical energy by plants. Through photosynthesis, plants take in CO_2 from the atmosphere and water from the soil, split off the oxygen atom from water, release oxygen gas back to the atmosphere, and combine the C atom with other C atoms and minerals, including N and phosphorus, to produce plant tissue and crop yield. After the crop is harvested, part of the plant is usually taken away from the field. Other plant material on the surface remains in the field as crop residue, which includes plant stems, leaves, and roots. Over time the plant material decomposes. Some molecules, those most readily decomposable, are quickly incorporated into microorganisms and other soil biota that use them as an energy source. Other plant materials, made of less easily decomposed materials such as lignin, become structural or metabolic litter. The organic material is broken down into any of three major pools: active pool (microbial biomass), slow pool (slowly decomposable humus), and passive pool (hardly decomposable humus) depending on its inherent decomposition rate as estimated by the lignin composition (Parton et al., 1993). Inputs from fertilizer application, precipitation and irrigation water are included in the N budget. Daily N fixation from plant is estimated as a fraction of daily plant uptake. Nitrogen is absorbed by plants, removed in harvested crops, and is dissolved in water or attached to particles that leave the field. EPIC simulates the transformation of NH_4^+ to NO_3^- through nitrification. Nitrate undergoes denitrification to produce N_2 and N_2O, and organic N undergoes mineralization (Cooter et al., 2012). However, C and N can also be lost in the form of leachates, eroded sediments or CO_2 emission.

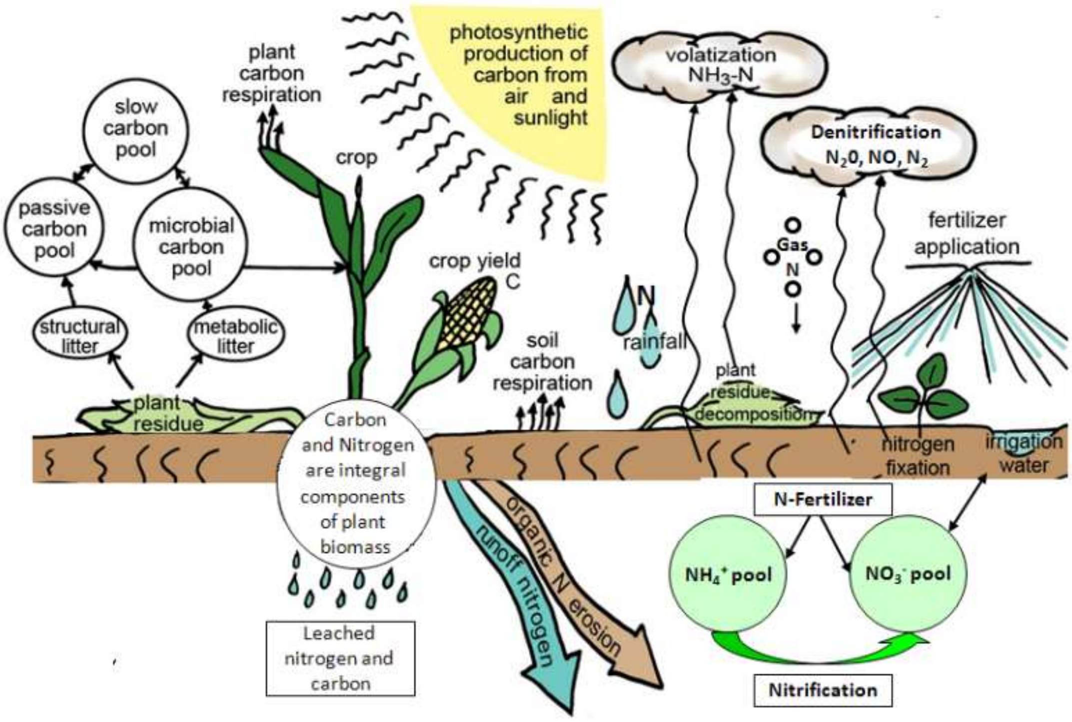


Figure 2-2 Biogeochemical components of the C and N budgets in EPIC (Cooter et al., 2012)

EPIC represents these factors using transformation rate controls exerted by the soil temperature and soil water equations. Tillage and other management operations are simulated to represent effects on decomposition rates. SOC is simulated by functions that convert crop residues, roots and organic amendments added to the soil. In Figure 2-3, the total C pool for C estimations in the soil consists of five compartments: structural litter, metabolic litter, microbial biomass, slow humus, and passive humus. Parton et al. (1987; 1993 and 1994) and Izaurralde et al. (2006) described the original Century model and the new C and N modules developed in EPIC as built on concepts from the Century model to connect the simulation of soil C dynamics to crop management, tillage methods, and erosion processes. The surface microbial pool turnover rate is independent of soil texture, while soil texture influences the turnover of active SOM (higher rates for sandy-soils) (as shown in Figure 2-3). The model assumes a 60% loss of C due to microbial respiration for surface microbes and 55% for all other layers. Allocation of C from lignin of structural litter to CO_2 is set at 0.3 while the rest is partitioned into slowly decomposable humus. In each of the processes, there are moisture and temperature controls on soil biological processes.

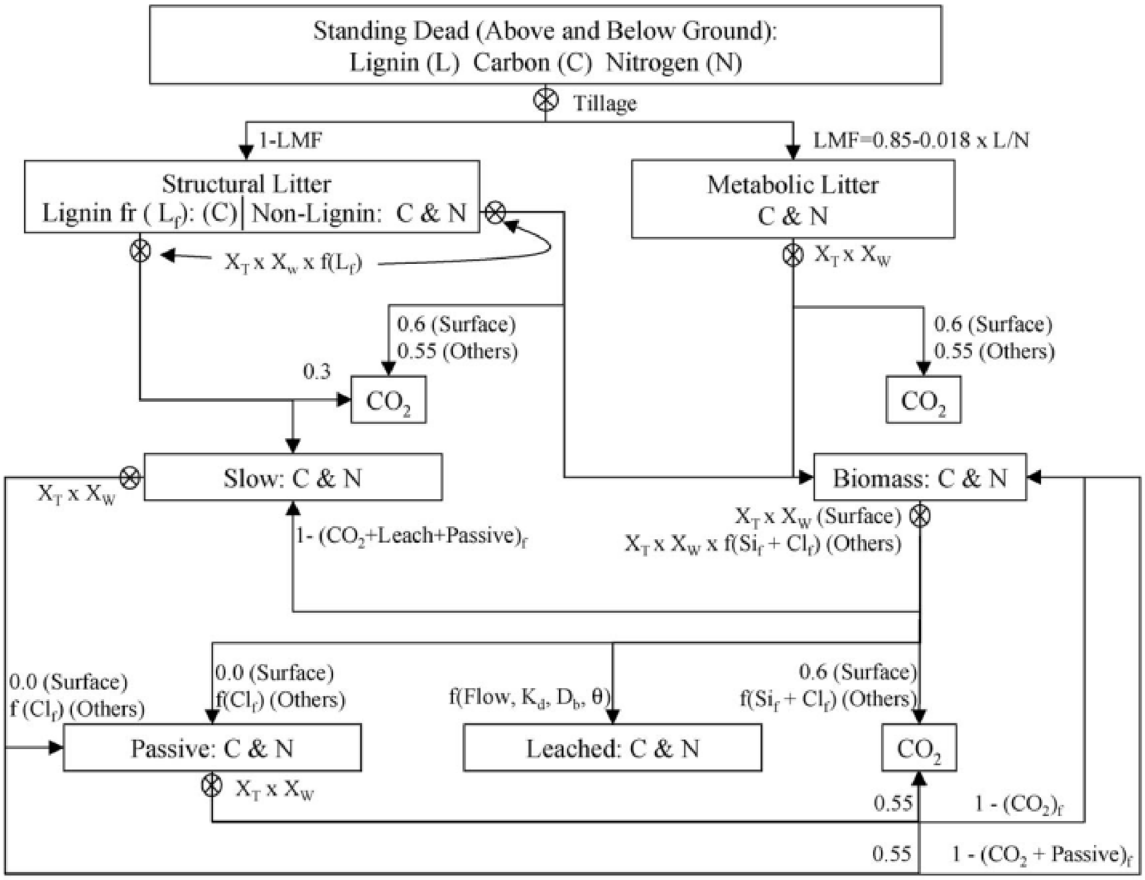


Figure 2-3 Carbon flows in EPIC. X_W and X_T refer to moisture and temperature control on soil biological processes, LMF = fraction of the litter that is metabolic (kg kg^{-1}) Lf = fraction of structural litter that is lignin (kg kg^{-1}); lower case f = “function of”, and subscript f = “fraction”; Sif = fraction of soil mineral component that is silt; Clf = fraction of soil mineral component that is clay; K_d = distribution coefficient of organic compounds between soil solid and liquid phases; DB = soil bulk density; θ = soil volumetric water content (Izaurralde et al., 2006)

Plant residues (shoots and roots) are partitioned into structural (resistant to decomposition) and metabolic (readily decomposable) plant material as a function of the initial residue lignin (L)-to-N (N) ratio (L:N) using the following equations:

$$LMF = 0.85 - 0.018 \times L/N \quad (23)$$

where *LMF* is the fraction of the litter that is metabolic (kg kg^{-1})

$$LSF = 1 - LMF \quad (24)$$

where *LSF* is the fraction of the litter that is structural (kg kg^{-1})

The model assumes that all C decomposition flows are associated with microbial activity and that microbial respiration occurs for each of these flows. Carbon leaving the active C is divided into four different flows which include microbial respiration, leaching of soluble organic C, stabilization of C in the slow and passive pool (equations (25) - (28)).

$$AB_{CO2} = 0.85 - 0.68 \times T \quad (25)$$

where AB_{CO2} is the fraction of C lost due to microbial respiration (the subsurface partitioning of biomass to CO_2), and *T* is the silt plus clay content (fraction)

$$C_{AL} = (H_2O_{(30)}/18) \times (0.01 + 0.04 \times T_s) \quad (26)$$

$$C_{AP} = 0.003 + 0.32 \times T_c \quad (27)$$

$$C_{AS} = (1 - C_{AP} - C_{AL} - AB_{CO2}) \quad (28)$$

where C_{AL} is the fraction of C lost due to organic leaching, C_{AP} is the fraction allocated to passive pool, C_{AS} is the fraction sent to the slow pool, $H_2O_{(30)}$ is the monthly water leached below the 30 cm soil depth (cm $month^{-1}$), T_S is the sand content (fraction), T_C is the clay content (fraction)

The C flows out of slow C are allocated to passive C and active C (equations (29) and (30)).

$$C_{SP} = 0.003 - 0.009 \times T_c \quad (29)$$

$$C_{SA} = (1 - C_{AP} - 0.55) \quad (30)$$

C_{SP} is the fraction of slow C allocated to passive pool, and C_{SA} is the fraction of slow C allocated to the active pool (55% of the C is lost due to microbial respiration).

Chapter 3

Practices sustaining soil organic matter and rice yield in a tropical monsoon region

3.1 Introduction

In general, carbon dioxide (CO_2) may be removed from the atmosphere by capturing it in various systems, such as through soil carbon sequestration (SCS) processes (Saree et al., 2012). Soil organic carbon (SOC) is the dominant component of soil organic matter (SOM), which is an important source of carbon for soil processes and a sink for carbon sequestration. Thus, any increase in SOC could significantly increase soil carbon (C) storage and mitigate greenhouse gases (GHGs) that contribute to global warming and climate change (West and Post, 2002). Rice fields represent high capacity sources of SCS (Pan et al., 2004; Lu et al., 2009). However, various land management practices, such as tillage, straw management, fertilization, irrigation, and crop rotation, significantly affect GHG emissions (Huang et al., 2004; Arunrat et al., 2016), SCS (Pan et al., 2009; Bhattacharyya et al., 2010), rice production (Parry et al., 2004; Wassmann and Dobermann, 2007), and food security (Nguyen, 2006).

In Thailand, rice (*Oryza sativa* L.) cropping is a major land use, and rice fields are distributed throughout most of the northeast region. In general, this region has rain-fed cultivation in the tropical monsoon area, where rice is grown once a year. Jasmine rice is mostly grown under rain-fed conditions in this region. Unfortunately, the soils are often described as universally infertile, with low inherent nutrient contents (Chantanaparb et al., 1976). The soil texture is sandy loam, and the SOC content is very low, ranging between 0.26% and 0.80%. The rate of SOC sequestration is very low (around 1.54 kg ha^{-1} yr^{-1}) compared with other regions (Limtong and Srikhajon, 2002). Thus, it is necessary to quantify C inputs to the soil, to determine whether they are sufficient to improve SOC over the long term. All of these soil constraints cause stunted growth, and have drastically reduced rice grain yield. In 2014, the average yield for jasmine rice in northeast Thailand is approximately 2.26 Mg ha^{-1} (OAE, 2014), which is the lowest in the country. Various studies have suggested that rice field management with rice cropping under irrigated, anaerobic conditions favors the accumulation of SOM (Zhang and He, 2004). Moreover, it is thought that SOM decomposes more slowly under anoxic conditions compared to oxic conditions (Sahrawat, 2004). Thus, it is likely that SOM may increase SOC and crop yields through certain land management practices, such as inputs of organic materials (manures) (Zhang et al., 2010) and chemical fertilizer application (Srinivasarao et al., 2012).

In humid and tropical regions, several studies have been published on SOC and rice yield. These studies recommend that current nutrient management should involve a combination of manure and chemical fertilizers to improve nutrient efficiency for plant uptake (Zhang et al., 2009; Zhao et al., 2013) and to increase crop yield (Witt et al., 2000; Surekha et al., 2003). For instance, in subtropical China, the addition of manure to the soil enabled 18% higher rice yield (Bi et al., 2009) than that of chemical fertilizer alone. The highest grain yield of rice was obtained when farmyard manure was applied at 10 Mg ha^{-1} combined with 120, 60, 45 kg ha^{-1} for N, P, and K, respectively, of sandy loam soil in India (Satyanaraya et al., 2002). However, these studies were obtained either short or long term agricultural experiments, which may be different between scientific experiments and the activities of farmers, in particular in developing countries, such optimal conditions are difficult to achieve (Maat, 2011). This is because increasing crop productivity and soil health on farmers' actual management practices are associated with the limitation of socio-economic factors of farmers' household (Linh et al., 2013). Only a study by Alam et al. (2013) have well done in Bangladesh, who evaluated the best management practices (BMP) integrated with farmers' crop management techniques in rice for productivity and profitability. Their results showed that 3-28% grain yield increases with BMP resulting in farmers' net profit increase of US$22 to 120 ha^{-1}. Nevertheless, soil characteristics were not taken into consideration in their study. It can be also affected by the different practices of farmer management, especially SOC have been described as a key indicator in soil fertility management (Loveland and Webb, 2003). Therefore, the investigation of farmers' actual practice effect on rice yield and SOC with their practices are limited in tropical monsoon area.

Any management practices should ensure that increasing yields will not destruct the ecology in the future. In order to be sustainable management of rice fields in tropical monsoon climates, it is necessary to understand current soil properties and land management practices to develop alternative management practices for maintaining soil quality and increasing in rice yield to ensure food security for the food demands of the growing population. Therefore, our study is the first detailed local analysis of how farmers' actual management practice factors influence rice yield and SOC. The objectives of this study were to (1) investigate the contents and distribution of rice yield and SOC under different land management practices, and (2) analyze the relationship between rice yield and SOC with pertinent management practices, i.e., manure and fertilizer.

3.2 Materials and methods

3.2.1 Description of the study area

The study area was in Thung Kula Sub-district, Suwannaphum District, and Roi-Et Province, located at 15° 28′ N, 103° 48′ E. Roi-Et soils are formed from washed deposits of sandstone and occur on the lower part of peneplains. The elevation ranges from 100 m to 200 m above sea level. The area has a tropical monsoon climate (Köppen 'Aw'). The major soil type in Roi-Et Province is Ultisol with >60% sand content; low SOC, ranging from 0.40%–1.29%;

and medium acid surface soil of pH 5.0–6.0 (LDD, 1991). There are six soil series: a) *Ki* (Kula Ronghai series): fine-loamy, mixed, active, isohyperthermic Typic Natraqualfs; b) *Nn* (Nakhon Phanom series): fine, kaolinitic, isohyperthermic Aeric Plinthic Paleaquults; c) *Ph* (Phan series): fine, kaolinitic, isohyperthermic Typic (Plinthic) Endoaqualfs; d) *Pm* (Phimai series): very fine, smectitic, isohyperthermic Ustic Endoaquerts; e) *Sp* (San Pa Tong series): coarse-loamy, siliceous, semiactive, isohyperthermic Typic (Kandic) Paleustults; and f) *Tt* (Tha Tum): fine, mixed, semiactive, isohyperthermic Aeric (Plinthic) Endoaqualfs (LDD, 2003) (Figure 3-1). In general, the soils are deep, and are characterized by different colors; however, the dominant colors are a grayish-brown or light brown sandy loam A horizon overlying a light brown grading to pinkish-gray sandy clay loam or loam kandic B horizon, which, in turn, overlies a light gray or whitish clay loam or clay C horizon. The soils are mottled throughout the profile, with strong brown or yellowish brown or dark brown and some yellowish red or red mottles being common in the subsoil. The reaction is medium acidic over strong to very strongly acidic (LDD, 2003). The study area was divided into small sub-areas to collect soil samples and determine land management characteristics using a polygonal grid measuring 0.01 × 0.01 degrees in size, and covering ~1 × 1 km. The total area was 59.45 ha covering 64 grids overall, consisting of 22.29 ha and 24 grids in irrigated areas and 37.16 ha and 40 grids in rain-fed areas (Figure 3-2). This is because rain-fed and irrigated agriculture areas have been used for land performance assessment (George, 1997) associated with the better nutrient and water management practices to increase crop production (Heng et al., 2005). Rice is primarily cultivated during the rainy season, between May to October, while a second rice crop is planted during the dry season, between November and April of the following year (OAE, 2014).

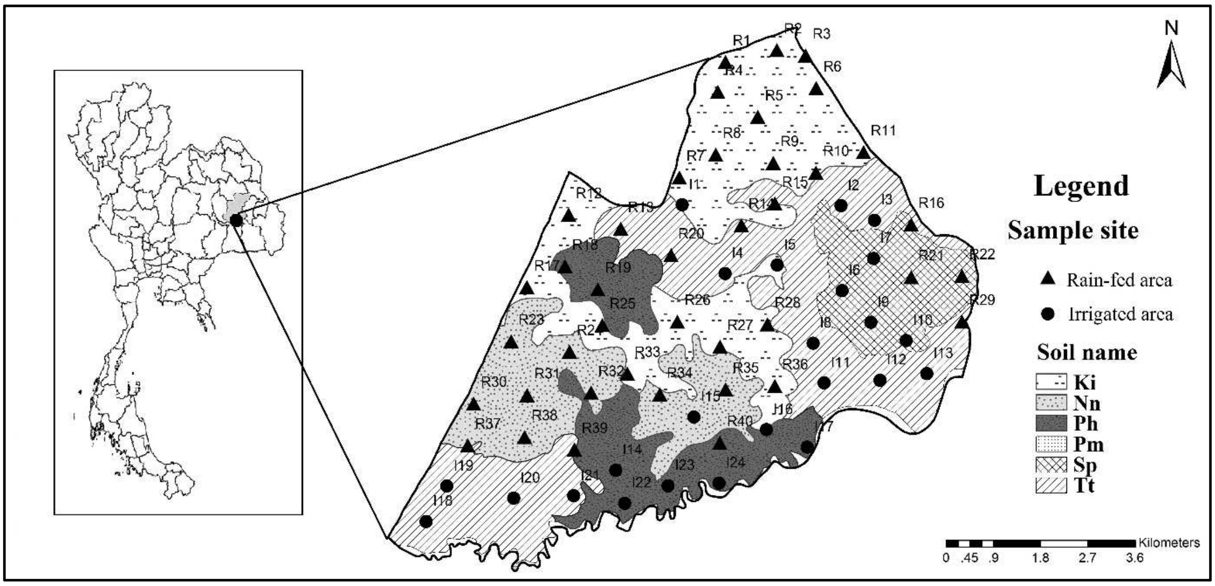


Figure 3-1 Study area and soil series (LDD, 2003)

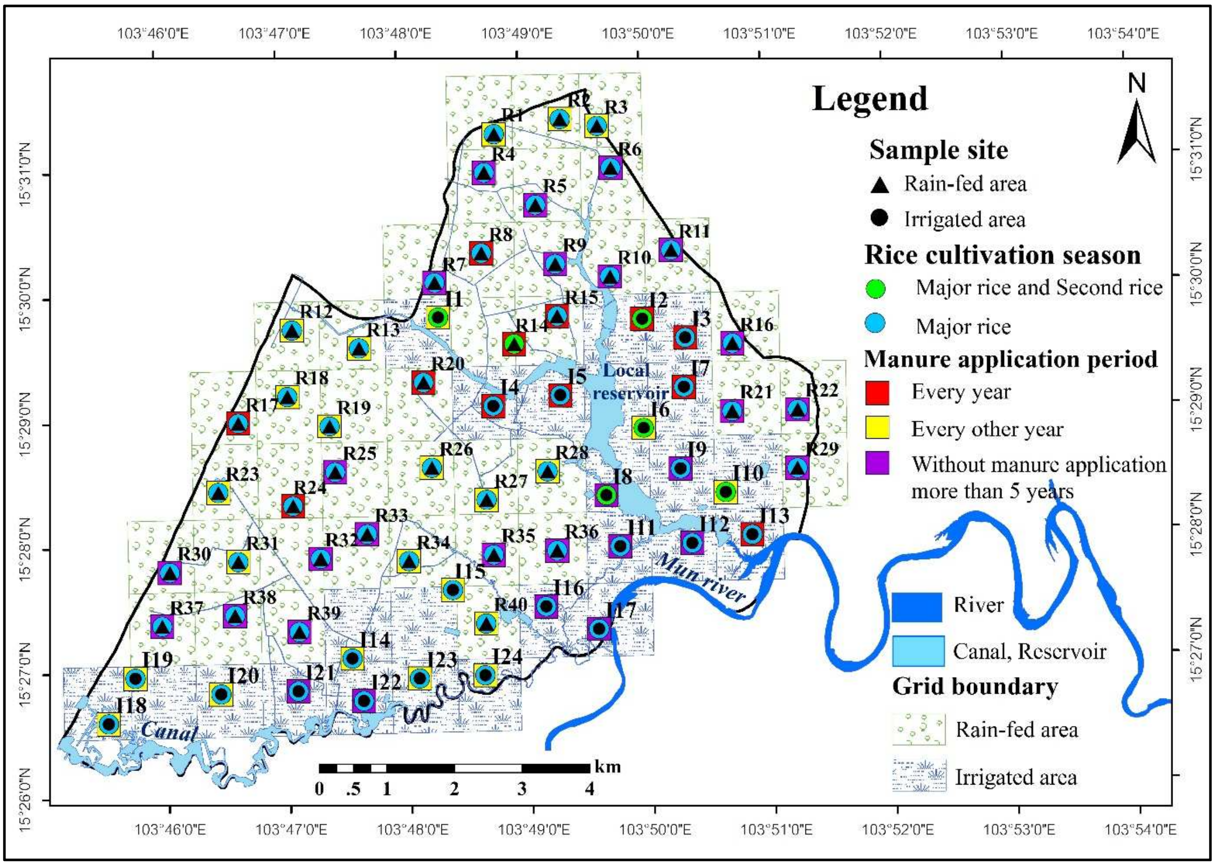


Figure 3-2 Overall land management practice in the study area

3.2.2 Questionnaires survey

The data were obtained over a 5 year period (2010–2014). Questionnaires were conducted at each sampling site to record the crop and management practices by farm owners. At 64 sites, 64 farmers were investigated their crop and land management data. Rice yields and management practice data (i.e., dates of planting and harvesting; rates of application of fertilizers, manure, pesticides, and irrigation; and field operations performed) were collected by our questionnaire survey in 2014 and from the record book for the standards for good agricultural practices (GAP) of farm owners over the 5 year study period (2010–2014), including both rainy and dry seasons. The record books were disseminated to the farmers by the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand to record their agricultural activities and report annually to GAP committee. The record book for GAP is very helpful for this study to obtain the precise data on operational practices. Rice yield data, fertilizer and manure application rates were averaged over a 5 years cultivation.

3.2.3 Rice cultivation practice

Based on the weather data from the Roi-Et Meteorological station (16° 03′ N, 103° 04′ E.), Thai Meteorological Department during 2004-2014, the monthly average air temperatures during the major rice season (rainy season) and second rice season (dry season) in 2014 reached 28.3 and 29.3 °C, respectively. These temperatures were higher than the averages of the preceding 10 years of 26.4 and 27.5 °C, respectively. Compared with the same period, the annual precipitation during the two rice planting seasons in 2014 was higher than that recorded in the preceding 10 years. The averages for the preceding 10 years were 164 and 73 mm, respectively, while those for 2014 were 223 and 88 mm yr^{-1}, respectively, for the two seasons. However, precipitation is a major limiting factor in rain-fed areas, where most farmers grow rice once a year, representing the major rice crop. Yet, farmers in some irrigated areas are able to grow rice twice a year, including the major and second rice crops. Only *Oryza sativa* was used in the study area. The main rice varieties recorded in this study were Khao Dawk Mali 105 (KDML 105), RD 6, and Suphanburi 60. KDML105 and RD 6 are strongly photoperiod sensitive and flower in late October, regardless of sowing time, while Suphanburi 60 is a non-photosensitive rice variety.

The main measures of conventional management in the study area are detailed below. First, during the growing period, both major rice crops and second rice crops were cultivated by the broadcast method and harvested by machine. Second, for tillage management, conventional tillage with a depth of 20 to 30 cm was applied by machine, distinguishing two different situations of wet and dry soil surface conditions. Third, for water management, continuous flooding and shallow flooding were used for irrigated and rain-fed areas, respectively. In irrigated areas, the fields were inundated with 10 to 15 cm standing water throughout the growing period and drained out or naturally dried 7 to 10 days before harvesting. In rain-fed areas, the soil was flooded temporarily, depending on rainfall or water pumping when no rain water was available. Fourth, for manure and chemical fertilizer application, cattle manure was often added to the soil as basal fertilizer once a year, usually after harvesting the previous crop or at the beginning of planting the next crop. Three patterns in the periodicity of manure application were detected during our study: every year, every other year, and without manure application for more than 5 years. Figure 3-2 presents the periodicity patterns of manure application. While the data for this study were gathered during 2010–2014, manure application in 2009 or planned application in 2015 were not considered. Therefore, the manure application in every year means the farmer applied the manure in rice field 5 years continually (2010, 2011, 2012, 2013, and 2014). The manure application in every other year means the farmer applied the manure in rice field in 2010, 2012, and 2014 or in 2011 and 2013. Meanwhile, without manure application for more than 5 years means the farmer did not apply the manure in rice field during 2010-2014. Chemical fertilizer was applied three times in the basal, tillering, and heading stages. The following types of chemical fertilizer were found in the study area: 46-0-0, 16-16-8, 16-20-0, 0-0-60, 15-15-15, and 16-8-8. The details of main management practices, rice yield, and SOC in each site are presented in Appendix Tables A-1 and A-2 for irrigated and rain-fed areas, respectively.

3.2.4 Soil sampling

Soil samples were collected during the dry season after the rice harvest (November, 2014). At each site, the soil horizons from 0 to 40 cm depth were identified by considering specific physical features; namely, color and texture. Three soil samples (replications) of each soil horizon were then collected. A total of 621 soil samples from 64 sites were collected.

3.2.5 Soil samples analysis

The soil texture (%) (sand, silt, and clay), bulk density, pH, OC, electrical conductivity (EC), CEC, and TN were analyzed in the laboratory. The physical and chemical properties of whole soils were determined using the procedures described by the National Soil Survey Center (1996). After a 24-hr drying period in an oven at 105 °C, soil bulk density was determined as the dry weight per unit volume of the soil core. Soil texture was determined by a hydrometer, and soil pH was determined in a 1:2.5 soil to water mixture by a pH meter. The EC in saturation paste extracts was measured following the method described by the United States Department of Agriculture (USDA, 1954). CEC was determined by the 1 N ammonium acetate (NH_4OAc) method. TN was measured by the Kjeldahl method. Soil was extracted by the Bray II method and, subsequently, the available phosphorus content was determined by the molybdate blue method (Bray and Kurtz, 1945). Extractable K, Ca, and Mg were leached from soil with NH_4OAc pH 7.0 and element concentrations were measured by atomic absorption spectrometry

(AAS) (Thomas, 1996). OC was determined by the method of Walkley and Black (1934). SOC stock was calculated by:

$$SOC = (BD \times OC \times D) \times 10000 \quad (1)$$

where *SOC* is soil organic carbon stock (Mg C ha^{-1}), *BD* is soil bulk density (Mg m^{-3}), *OC* is organic carbon content (%), and *D* is soil sampling depth (m).

3.2.6 Statistical analysis

Statistical analyses of the data were performed using SPSS (Version 20.0, USA). Mean and standard deviation values were used to represent rice yield and SOC in different areas. Differences in rice yield and SOC between irrigated and rain-fed areas were analyzed using a *t*-test and least significant difference (LSD) test ($p < 0.05$). Rice yield, SOC, and the main management practice were tested for collinearity. Tolerance (TOL) and the variance inflation factor (VIF) were used as the two important indices for multicollinearity diagnosis. A value of TOL is smaller than 0.1, while a value of VIF is greater than 10; this value indicates the level of serious multicollinearity between independent variables (Bai et al., 2010). Simple linear regression analysis was used to find the relationship between two variables by fitting a linear equation. Standardized Major Axis Tests & Routines (SMATR) version 2.0 was performed to compare the significant differences between irrigated and rain-fed areas. Subsequently, stepwise multiple regression analysis was conducted to evaluate the relationships of rice yield with the main management practice. The relationships between different soil properties and SOC were expressed using Pearson's correlation coefficient.

3.3 Results

3.3.1 Farmers' management practices

For all sites, the field management practices of rice cultivation are shown in Tables 3-1 and 3-2 for irrigated and rain-fed areas, respectively. The average manure application rate was 2.23 and 1.15 Mg ha^{-1} yr^{-1} for sites in irrigated and rain-fed areas, respectively, and was significantly higher in the irrigated areas compared to the rain-fed areas (p = 0.012). Considering the periods of manure application, in the irrigated areas, the average manure application rate was 3.57, 2.03, and 0 Mg ha^{-1} yr^{-1} for every year, every other year, and without more than 5 years application, respectively. Meanwhile, the average manure application rate of 2.30, 2.12, and 0 Mg ha^{-1} yr^{-1} were found for every year, every other year, and without more than 5 years application, respectively for rain-fed areas. There was no significant difference between the irrigated and rain-fed areas when manure application periods were considered. Based on Oo et al. (2010) reported that N, P, K concentrations in the manure were 1.32%, 0.57%, and 0.93%, respectively, at the experimental field of Khon Kaen University, Thailand. This study used these values to estimate the N, P, K contents in the manure of each site due to their study was obtained in the same region with our study area, which can be assumed that the factors affecting manure characteristics (i.e. animal species, diet, digestibility, housing, and environment) are quite similar. The average amount of N, P and K applications in manure was 44.06, 19.03, and 31.04 kg ha^{-1} yr^{-1} for irrigated areas, and 30.29, 13.08, and 21.33 kg ha^{-1} yr^{-1} for rain-fed areas, respectively. The statistical results revealed that the quantity of N, P and K applications in manure was significantly different between irrigated and rain-fed areas ($p < 0.01$) (Table 3-3).

The fertilizer application rate across all sites ranged from 150 to 400 kg ha^{-1} yr^{-1}, with an average of 280 kg ha^{-1} yr^{-1}. The N application rate ranged from 26.08 to 113.06 kg ha^{-1} yr^{-1} across sites, with averages of 88.74 and 76.44 kg ha^{-1} yr^{-1} for irrigated and rain-fed areas, respectively. The P and K application rate ranged from 0.00 to 49.04 and 0.00 to 71.04 kg ha^{-1} yr^{-1} across sites for irrigated and rain-fed areas, respectively. The average P and K application rate was 31.06 and 24.07 kg ha^{-1} yr^{-1} for irrigated areas and 14.45 and 12.04 kg ha^{-1} yr^{-1} for rain-fed areas (Tables 3-1 and 3-2). A highly significant difference in the fertilizer application rate was obtained between the irrigated and rain-fed areas (p = 0.002), with averages of 320 and 260 kg ha^{-1} yr^{-1}, respectively. Statistic results showed that the total amount of fertilizer application and N and P application rates were highly significantly different between irrigated and rain-fed areas (p < 0.01); however, there was no significant difference in the K application rate between irrigated and rain-fed areas (Table 3-3).

Table 3-1 Main management practices, rice yield, and SOC in irrigated areas (n = 24)

Site No.	Rice season*	Rice yield (Mg ha^{-1} yr^{-1})	SOC (Mg C ha^{-1})	Chemical fertilizer application rate				Manure application rate	
				Total amount applied (kg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})			Total amount applied (Mg ha^{-1} yr^{-1})	Manure application period
					N	P	K		
I2	M[2]	4.6	124.4	394	100.04	34.28	39.04	4.83	Every year
	S[3]	3.24	-	294	80.94	32.2	8	0	
I3	M[2]	4.92	129.87	395	99.64	38.68	31.64	4.85	
I4	M[1]	3.84	104.55	351	89.75	40.53	15.69	4.43	
I5	M[1]	3.93	100.23	351	94.52	33.56	21.88	4.41	
I7	M[1]	3.74	57.62	288	87.48	25.24	9.52	2.79	
I13	M[1]	3.76	52.89	369	92.44	30.96	40.48	3.65	
I1	M[1]	3.41	37.80	362	97.22	42.20	8	3.32	Every other year
	S[3]	2.3	-	294	80.94	32.20	8	0	
I6	M[1]	3.86	64.64	357	98.52	38.56	10.48	2.78	
	S[3]	2.93	-	307	89.52	28.80	15	0	
I10	M[2]	4.62	52.13	362	102.92	37.16	10.48	3.63	
	S[3]	2.86	-	307	84.82	23.04	15.04	0	
I14	M[1]	2.43	39.42	344	93.34	30.04	20.04	3.33	
I15	M[2]	3.65	49.18	338	88.78	36.80	19	2.66	
I18	M[1]	1.95	23.71	332	87.69	30.95	20.95	2.57	
I19	M[2]	2.04	21.43	288	87.48	26.00	8	2.58	
I20	M[1]	2.95	45.97	338	95.48	35.24	9.52	2.65	
I23	M[2]	1.84	11.15	281	73.96	31.20	15	2.47	
I24	M[1]	1.8	17.03	269	68.44	31.20	15	2.46	
I8	M[1]	3.69	49.41	288	81.78	32.56	2.48	0	Without manure application for more
	S[3]	3.1	-	331	92.26	35.24	9.52	0	
I9	M[2]	3.32	33.37	293	86.18	27.16	10.48	0	
I11	M[1]	1.97	36.89	282	80.32	30.10	7.5	0	

I12	M[1]	2.08	34.41	338	88.59	31.85	21.85	0	than 5 years
I16	M[1]	1.58	10.11	250	79.30	19.04	9.52	0	
I17	M[1]	1.5	10.57	250	85.00	16.00	8	0	
I21	M[2]	1.56	14.66	263	90.98	16.00	8	0	
I22	M[2]	1.65	9.12	263	85.95	16.95	16.95	0	

* M = major rice; S = second rice, [1] KDML105 rice; [2] RD 6 rice; [3] Suphanburi 60 rice

Table 3-2 Main management practices, rice yield, and SOC in rain-fed areas (n = 40)

Site No.	Rice season*	Rice yield (Mg ha^{-1} yr^{-1})	SOC (Mg C ha^{-1})	Chemical fertilizer application rate				Manure application rate	
				Total amount applied (kg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})			Total amount applied (Mg ha^{-1} yr^{-1})	Manure application period
					N	P	K		
R14	M[1]	3.62	101.38	401	95.48	36	45.8	2.8	Every year
	S[3]	2.49	-	269	73.04	29.8	8	0	
R15	M[1]	3.78	114.31	395	104.6	45.88	11.04	2.8	
R8	M[1]	3.52	112.04	401	113.06	35.6	8	2.8	
R20	M[1]	3.45	69.43	288	81.78	27.8	12	2.6	
R24	M[2]	3.35	63.96	294	85.71	29.45	9.45	2.6	
R17	M[1]	3.28	77.87	369	98.34	42.84	9.52	2.5	
R19	M[1]	3.37	59.29	281	83.26	25	15	2.62	Every other year
R18	M[1]	3.19	50.57	376	85.56	22.08	71.04	2.55	
R12	M[1]	3.2	53.77	388	103.48	38	8	2.5	
R13	M[2]	3.15	53.13	369	98.34	42.84	9.52	2.5	
R1	M[2]	2.53	28.28	388	97.78	49.04	9.52	2.4	
R2	M[1]	2.49	22.54	269	73.04	29.8	8	2.4	
R3	M[1]	2.48	18.75	262	80.41	22.15	12.15	2.3	
R28	M[1]	2.22	21.84	269	70.74	16	38	2.13	
R27	M[1]	2.14	25.46	200	62	18	4	2.13	
R26	M[1]	2.11	18.93	188	55.98	15.5	11.5	2.16	
R31	M[2]	2.06	22.55	169	57.04	12.56	2.48	1.7	
R34	M[1]	2.05	19.4	169	56.66	11.9	5.7	1.6	
R23	M[1]	2.04	18.55	169	52.94	13.7	7.5	1.3	
R40	M[2]	2.03	13.23	169	56.54	11.3	7.5	1.5	
R32	M[1]	2.6	30.1	369	86.74	35.24	39.52	0	Without manure application
R33	M[1]	2.53	29.77	351	97.25	36.29	14.17	0	
R39	M[1]	2.48	28.24	345	87.86	36.64	20.92	0	
R4	M[1]	2.22	26.25	263	72.08	28.6	8	0	

R5	M[1]	2.17	20.04	263	87.08	20.08	5.04	0	for more than 5 years
R7	M[1]	2.14	21.21	257	76.82	26.08	3.04	0	
R9	M[1]	2.11	32.96	250	70	27.24	5.52	0	
R38	M[1]	2.08	13.63	188	65.47	10.73	7.69	0	
R37	M[2]	2	17.03	176	58.16	13.68	3.04	0	
R36	M[2]	2	8.86	226	71.86	19.12	1.52	0	
R35	M[1]	1.98	8.75	238	67.39	24.15	10.35	0	
R25	M[1]	1.96	14.09	351	97.56	38.08	9.04	0	
R30	M[1]	1.9	21.50	181	64.35	9.61	7.13	0	
R10	M[1]	1.8	9.87	181	58.46	13.7	7.5	0	
R16	M[1]	1.71	6.60	238	79.48	16	8	0	
R6	M[2]	1.66	9.48	238	78.48	15	15	0	
R11	M[1]	1.53	7.84	194	64.94	12.96	6.48	0	
R29	M[2]	1.42	4.4	163	26.08	28.6	8	0	
R22	M[1]	1.34	3.76	150	69	0	0	0	
R21	M[2]	1.29	3.78	150	69	0	0	0	

* M = major rice; S = second rice, [1] KDML105 rice; [2] RD 6 rice; [3] Suphanburi 60 rice

Table 3-3 Comparison of the annual main management practices between irrigated and rain-fed areas (Mean ± SD)

Pertinent management practice	**Irrigated area**	**Rain-fed area**	*p*-values
Manure application rate			
All sites (Mg ha^{-1} yr^{-1})	2.23±1.75 (n = 24)	1.15±1.20 (n = 40)	0.012
Manure application every year (Mg ha^{-1} yr^{-1})	3.57±1.73 (n = 7)	2.30±1.02 (n = 7)	0.128
Manure application every other year (Mg ha^{-1} yr^{-1})	2.03±1.37 (n = 14)	2.12±0.43 (n = 14)	0.807
Without manure application for more than 5 years (Mg ha^{-1} yr^{-1})	0	0	-
Manure application rate			
N (kg ha^{-1} yr^{-1})	44.06±11.44 (n = 16)	30.29±5.90 (n = 20)	0.000
P (kg ha^{-1} yr^{-1})	19.03±4.94 (n = 16)	13.08±2.55 (n = 20)	0.000

K (kg ha^{-1} yr^{-1})	31.04±8.06 (n = 16)	21.33±4.16 (n = 20)	0.000
Chemical fertilizer application rate			
Total (kg ha^{-1} yr^{-1})	320±45.17 (n = 24)	260±84.37 (n = 40)	0.002
N (kg ha^{-1} yr^{-1})	88.74±8.03 (n = 24)	76.44±17.61 (n = 40)	0.000
P (kg ha^{-1} yr^{-1})	31.06±7.36 (n = 24)	24.07±12.12 (n = 40)	0.004
K (kg ha^{-1} yr^{-1})	14.45±9.33 (n = 24)	12.04±13.50 (n = 40)	0.380

3.3.2 Soil characteristics

3.3.2.1 Soil physical and chemical properties

There were no significant differences in the sand, silt, and clay contents, and finer soil particles (silt + clay) between irrigated and rain-fed areas; however, BD was significantly different ($p < 0.05$; Table 3-4). Most of the soils in the study area had a sandy texture. Clay content tended to accumulate in the subsoil layers (10–40 cm), with a simultaneous decrease in sand content. In comparison, silt content was higher in the soil surface layer (0–10 cm), and slightly decreased with increasing depth (Figure 3-3). The amount of finer soil particles was lower in the soil surface layer, and steadily increased with increasing depth (Table 3-5), ranging from 3.98 to 53.00%, with an average of 27.40%. The sand, silt, and clay contents had ranges of 47.00 to 96.02, 0.10 to 23.90, and 2.00 to 32.40%, respectively, and average values of 72.60, 12.00, and 15.40%, respectively. BD ranged from 0.84 to 1.99 Mg m^{-3}, and mean values of 1.38 and 1.43 Mg m^{-3} for irrigated and rain-fed areas, respectively. In each profile, surface soil had slightly lower BD than the subsoil, with this value increasing at a depth between 10 and 40 cm (Table 3-5).

There were significant differences in pH, TN, OC, ECe, and CEC, while available P, exchangeable K, Ca, and Mg were not significantly different between irrigated and rain-fed areas ($p < 0.05$; Table 3-4). The pH values of the soil ranged from extremely acidic to slightly acidic (pH 3.86 to 6.66). The mean values of soil pH were 5.07 and 5.03 for irrigated and rain-fed areas, respectively. At all sites, there was higher pH in the surface soil and slightly lower pH in the subsoil. The amount of TN was very low in all soils studied, ranging from 0.001 to 0.095%, with averages of 0.032 and 0.019% for irrigated and rain-fed areas, respectively. A decrease in TN content with increasing depth was observed throughout the study area. The amount of OC in all studied soils was very low, ranging from 0.02 to 3.230%, with averages of 1.10 and 0.63% for irrigated and rain-fed areas, respectively. A decrease in OC content with increasing depth was observed throughout the study area. A range of ECe values (0.01–0.17 dS m^{-1}) was observed, with an average of 0.071 dS m^{-1} in the soils of the study area. Surface soils had a higher value, while the underlying layer had slightly lower values. The average ECe values in the soils of irrigated and rain-fed areas were 0.078 and 0.067 dS m^{-1}, respectively. All soils were non-saline. The CEC of the studied soils was very low to moderately low, with values ranging from 2.31 to 7.52 cmolc kg^{-1}. The average value of the CEC for all samples was 4.72 cmolc kg^{-1}, with averages of 4.95 and 4.59 cmolc kg^{-1} for irrigated and rain-fed areas, respectively. The sandy nature of the soils, with low clay and OM contents, was responsible for the soils in all areas having a low CEC. CEC values increased with depth (Table 3-5; Figure 3-4).

Table 3-4 Comparison of soil physical and chemical properties between irrigated and rain-fed areas for all soil depths (0-40 cm) (Mean ± SD)

	BD (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Silt+Clay (%)	pH	TN (%)	OC (%)	ECe (dSm^{-1})	CEC (cmol ckg^{-1})	Avail.P (mg kg^{-1})	Exch.K (mg kg^{-1})	Exch.Ca (mg kg^{-1})	Exch.Mg (mg kg^{-1})
Irrigated area (n = 24)	1.38± 0.23	74.64± 9.96	11.92± 6.18	13.44± 6.03	25.36± 9.96	5.07± 0.63	0.032± 0.028	1.10± 0.96	0.078± 0.030	4.95± 0.74	4.84± 3.24	41.12± 44.82	106.55± 121.36	22.96± 57.71
Rain-fed area (n = 40)	1.43± 0.21	71.42± 9.29	12.05± 5.85	16.53± 6.47	28.58± 9.29	5.03± 0.70	0.019± 0.021	0.63± 0.71	0.067± 0.037	4.59± 0.99	4.96± 3.08	46.31± 49.44	196.20± 165.10	23.41± 25.08
p-values	0.034	0.063	0.086	0.054	0.06	0.037	0.015	0.028	0.037	0.033	0.35	0.173	0.687	0.41

BD = Bulk density, TN = Total nitrogen, OC = Organic carbon, ECe = Electrical conductivity, CEC = Cation exchange capacity, Avail. P = Available phosphorous, Exch. K = Exchangeable potassium, Exch. Ca = Exchangeable calcium, Exch. Mg = Exchangeable magnesium

Table 3-5 Average values of soil physical and chemical properties at four different depths, 0–10, 10–20, 20–30, and 30-40 cm from all sites (Mean ± SD)

Depth (cm)	SOC (Mg C ha^{-1})	BD (Mg m^{-3})	Sand (%)	Silt (%)	Clay (%)	Silt+Clay (%)	Texture	pH	TN (%)	OC (%)	ECe (dSm^{-1})	CEC (cmol ckg^{-1})	Avail.P (mg kg^{-1})	Exch.K (mg kg^{-1})	Exch.Ca (mg kg^{-1})	Exch.Mg (mg kg^{-1})
0-10	13.91± 13.49	1.26± 0.16	77.92± 5.78	11.01± 5.12	11.07± 3.17	22.08± 5.78	Sandy loam	5.28± 0.81	0.041± 0.027	1.40± 0.91	0.085± 0.042	4.74± 1.03	5.08± 2.57	59.68± 56.81	136.35± 106.48	16.57± 21.56
10-20	11.71± 12.88	1.39± 0.19	74.48± 10.13	11.35± 6.45	14.17± 5.61	25.52± 10.13	Sandy loam	5.10± 0.56	0.020± 0.021	0.70± 0.71	0.067± 0.030	4.64± 0.85	5.93± 3.45	40.41± 43.94	158.87± 152.99	25.08± 50.66
20-30	9.45± 10.41	1.58± 0.20	66.11± 8.82	14.01± 5.38	19.88± 6.36	33.89± 8.82	Sandy loam	4.77± 0.52	0.014± 0.018	0.45± 0.63	0.066± 0.032	4.74± 0.89	3.91± 3.18	30.12± 15.02	207.47± 208.59	31.62± 48.12
30-40	9.75± 11.61	1.57± 0.16	65.62± 6.94	12.95± 6.61	21.43± 5.62	34.38± 6.94	Sandy clay loam	4.80± 0.57	0.009± 0.011	0.25± 0.35	0.054± 0.023	4.86± 0.91	3.53± 2.51	40.93± 57.39	170.97± 164.88	21.63± 27.16

BD = Bulk density, TN = Total nitrogen, OC = Organic carbon, ECe = Electrical conductivity, CEC = Cation exchange capacity, Avail. P = Available phosphorous, Exch. K = Exchangeable potassium, Exch. Ca = Exchangeable calcium, Exch. Mg = Exchangeable magnesium

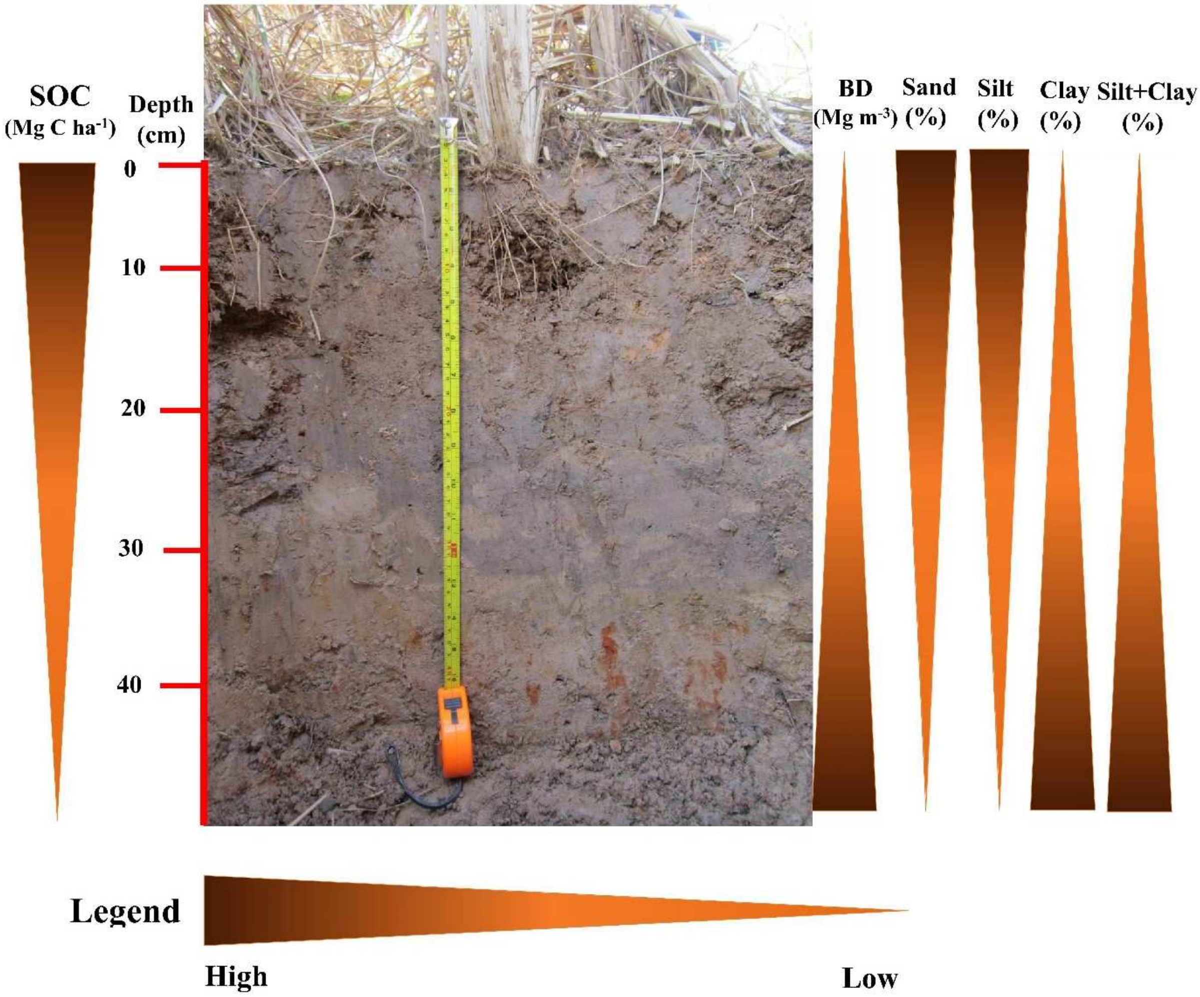


Figure 3-3 The distribution of soil physical properties in the soil profile. The example soil profile is from site R14. BD = Bulk density (Mg m^{-3})

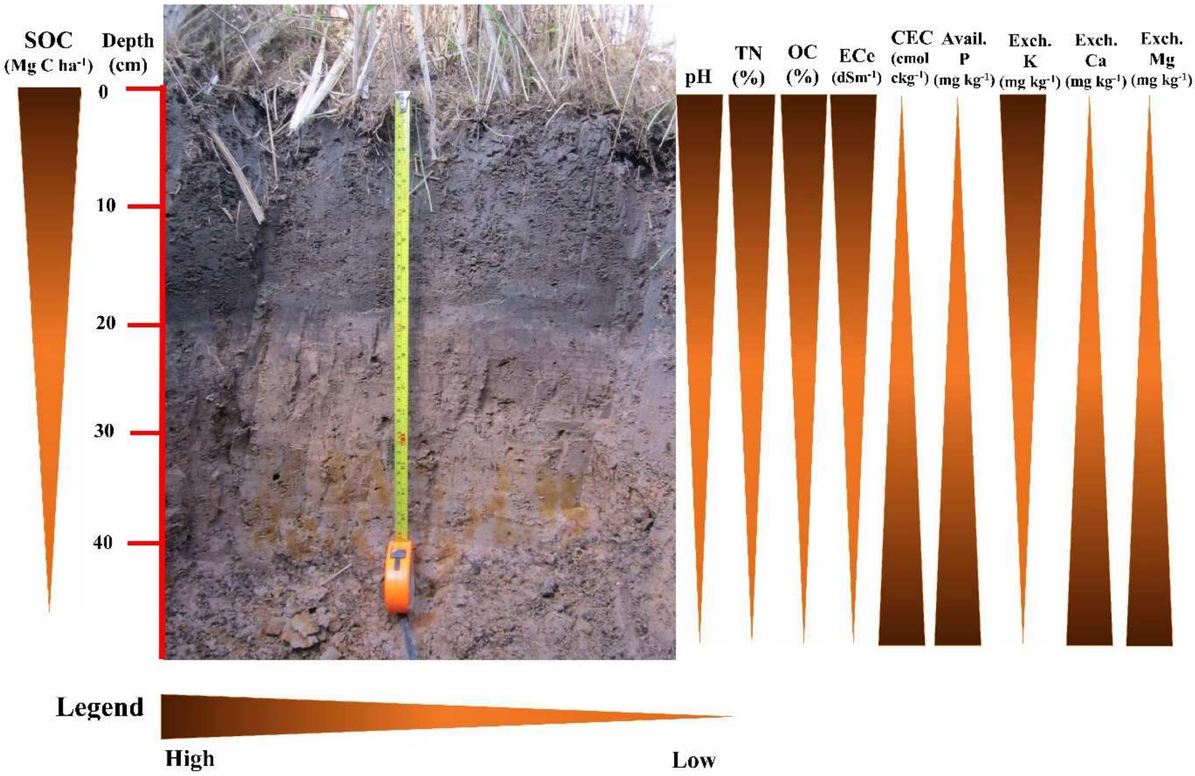


Figure 3-4 Distribution of soil chemical properties in the soil profile. The example soil profile is from site I2. TN = Total nitrogen (%), OC = Organic carbon (%), ECe = Electrical conductivity (dSm^{-1}), CEC = Cation exchange capacity (cmol ckg^{-1}), Avail. P = Available phosphorous (mg kg^{-1}), Exch. K = Exchangeable potassium (mg kg^{-1}), Exch. Ca = Exchangeable calcium (mg kg^{-1}), Exch. Mg = Exchangeable magnesium (mg kg^{-1})

3.3.2.2 Relationship among the soil physical and chemical properties with SOC

The distribution of individual BD and clay contents at all sites did not show any significant correlation with SOC; however, sand, silt contents and finer soil particles were significantly related to SOC ($r = -0.284^{*}$, 0.362^{**} and 0.284^{*}, respectively, $p < 0.05$). Sand content was negatively correlated with SOC, while BD, clay and silt contents, and finer soil particles were positively correlated with SOC (Table 3-6).

Statistic results showed that the pH, TN, OC and ECe values showed a highly positive correlation with SOC, with r values of 0.474^{**}, 0.641^{**}, 0.959^{**}, and 0.583^{**}, respectively. On the other hand, CEC had a highly negative correlation ($r = -0.464^{**}$) with SOC in all sites (Table 3-6). All of these results indicate that soils were more fertile in irrigated areas compared to rain-fed areas. Most of the arable soils in the study area had a sandy texture, while an accumulation of clay content was observed in the subsoil layers (10–40 cm), with a simultaneous decrease in sand content.

Table 3-6 Correlation matrix of soil physical and chemical properties with SOC at all sites (n = 64)

Property	BD	Sand	Clay	Silt	Silt+ Clay	pH	TN	OC	ECe	CEC	Avail. P	Exch. K	Exch. Ca	Exch. Mg	SOC
BD	1.00														
Sand	-0.413**	1.00													
Clay	0.346**	-0.671**	1.00												
Silt	0.284*	-0.817**	0.121	1.00											
Silt+Clay	0.413**	-1.000**	0.671**	0.817**	1.00										
pH	0.009	-0.12	0.117	0.07	0.12	1.00									
TN	-0.049	0.035	-0.242	0.141	-0.035	0.373**	1.00								
OC	-0.02	-0.235	-0.057	0.359**	0.235	0.473**	0.672**	1.00							
ECe	-0.15	-0.228	0.101	0.227	0.228	0.544**	0.381**	0.619**	1.00						
CEC	-0.156	0.271*	-0.24	-0.176	-0.271*	-0.485**	-0.214	-0.430**	-0.263*	1.00					
Avail. P	-0.260*	0.114	-0.041	-0.121	-0.114	-0.11	-0.007	-0.197	-0.002	0.196	1.00				
Exch. K	0.205	-0.261*	0.207	0.188	0.261*	-0.112	0.019	-0.073	-0.226	0.091	0.047	1.00			
Exch. Ca	0.06	-0.308*	0.295*	0.183	0.308*	-0.038	-0.250*	-0.068	0.06	-0.195	-0.011	-0.129	1.00		
Exch. Mg	-0.09	-0.177	0.049	0.199	0.177	-0.047	-0.146	0.022	0.099	-0.059	0.063	-0.237	0.320**	1.00	
SOC	0.1	-0.284*	0.025	0.362**	0.284*	0.474**	0.641**	0.959**	0.583**	-0.464**	-0.212	-0.006	-0.051	-0.025	1.00

BD = Bulk density (Mg m^{-3}), Sand = Sand content (%), Silt = Silt content (%), Clay = Clay content (%), Silt+Clay = Silt+Clay contents (%), TN = Total nitrogen (%), OC = Organic carbon (%), ECe = Electrical conductivity (dSm^{-1}), CEC = Cation exchange capacity (cmol ckg^{-1}), Avail. P = Available phosphorous (mg kg^{-1}), Exch. K = Exchangeable potassium (mg kg^{-1}), Exch. Ca = Exchangeable calcium (mg kg^{-1}), Exch. Mg = Exchangeable magnesium (mg kg^{-1}), and SOC = Soil organic carbon (Mg C ha^{-1}). * = Correlation is significant at 0.05 probability level, ** = Correlation is significant at 0.01 probability level

3.3.3 Relationships between farmers' management practices, rice yield, and SOC

To explore potential multicollinearity among the explanatory variables, TOL and VIF were tested. When rice yield was assigned as the dependent variable, the TOL and VIF values for all variables ranged from 0.472 to 0.826 and 1.210 to 2.117, respectively. Ranges of 0.472 to 0.826 and 1.210 to 2.117 were found for TOL and VIF values, respectively, when SOC was assigned as the dependent variable. Therefore, multicollinearity was not a serious problem in this study.

Major rice season yields ranged from 1.29 to 4.92 Mg ha^{-1} yr^{-1} across sites, with averages of 2.95 and 2.37 Mg ha^{-1} yr^{-1} in irrigated and rain-fed areas, respectively. Second rice season yields ranged from 2.11 to 3.24 Mg ha^{-1} yr^{-1}, with averages of 2.85 and 2.49 Mg ha^{-1} yr^{-1} in irrigated and rain-fed areas, respectively. The average yields of KDML105, RD 6 and Suphanburi 60 rice were 2.83, 3.13 and 2.89 Mg ha^{-1} yr^{-1} in irrigated areas, respectively, while 2.45, 2.15 and 2.49 Mg ha^{-1} yr^{-1} in rain-fed areas, respectively (Tables 3-1 and 3-2). There was no significant difference in yield potential among KDML105, RD 6, and Suphanburi 60 rice. Although a significant difference between irrigated and rain-fed areas was obtained for major rice season yields ($p < 0.05$; Table 3-7), a similar result was not obtained for second rice season yields. This is because a second rice crop was only planted at one site (site R14), resulting in the sample size being too small for rain-fed areas. For the whole crop year, the average rice yield was 2.93 and 2.38 Mg ha^{-1} yr^{-1} in irrigated and rain-fed areas, respectively, with a significant difference being found between irrigated and rain-fed areas ($p < 0.05$; Table 3-7).

SOC values ranged from 3.76 to 129.87 Mg C ha^{-1} in all sites, with averages of 47.11 and 32.09 Mg C ha^{-1} for irrigated and rain-fed areas, respectively. There was a slight difference in SOC between irrigated and rain-fed areas ($p < 0.1$; Table 3-7). There was a significant correlation between rice yield and SOC both in irrigated ($R^2 = 0.72$, $p < 0.01$) and in rain-fed areas ($R^2 = 0.85$, $p < 0.01$) (Figure 3-5), with the slopes of these regression equations being significantly different. There were also significant relationships between rice yield and the application rates of N, P and K (Figure 3-6), and manure application rate (Figure 3-7). Application rates of N, P and K were positively correlated with rice yield in irrigated areas (R^2 = 0.53, 0.40, and 0.21, respectively; $p < 0.01$) (Figure 3-6(a)) and in rain-fed areas (R^2 values of 0.50, 0.49, and 0.17, respectively; $p < 0.01$) (Figure 3-6(b)). Manure application every year and every other year were positively correlated with rice yield in irrigated areas (R^2 = 0.53 and 0.43, $p < 0.01$, respectively) (Figure 3-7(a)) and in rain-fed areas (R^2 = 0.76 and 0.66, $p < 0.01$, respectively) (Figure 3-7(b)). Although without manure application for more than 5 years was assumed to be no manure application (0 Mg ha^{-1} yr^{-1}) for the period of this study (Figures 3-7(a) and (b)), rice yield ranged from 1.50 to 3.69 and 1.29 to 2.60 Mg ha^{-1} yr^{-1} for irrigated and rain-fed areas, respectively (Tables 3-1 and 3-2). There are two reasons for no manure application. Firstly, some farmers do not feed their own cattle animals, so they do not have the manure for application. Secondly, other farmers have less manure in their houses, so they need to store more manure and apply in the soil together once having enough manure. Meanwhile, they neither gather up the manure scattered outdoors nor from their neighbors.

Table 3-7 Comparison of rice yield and SOC between irrigated and rain-fed areas (Mean ± SD)

	Rice yield (Mg ha^{-1} yr^{-1})			**SOC (Mg C ha^{-1})**
	Major rice	Second rice	Whole crop year	
Irrigated area	2.95±1.12 (n = 24)	2.85±0.44 (n = 5)	2.93±1.03 (n = 29)	47.11±35.29 (n = 24)
Rain-fed area	2.37±0.67 (n = 40)	2.49 (n = 1)	2.38±0.66 (n = 41)	32.09±29.03 (n = 40)
p-values	0.030	-	0.015	0.086

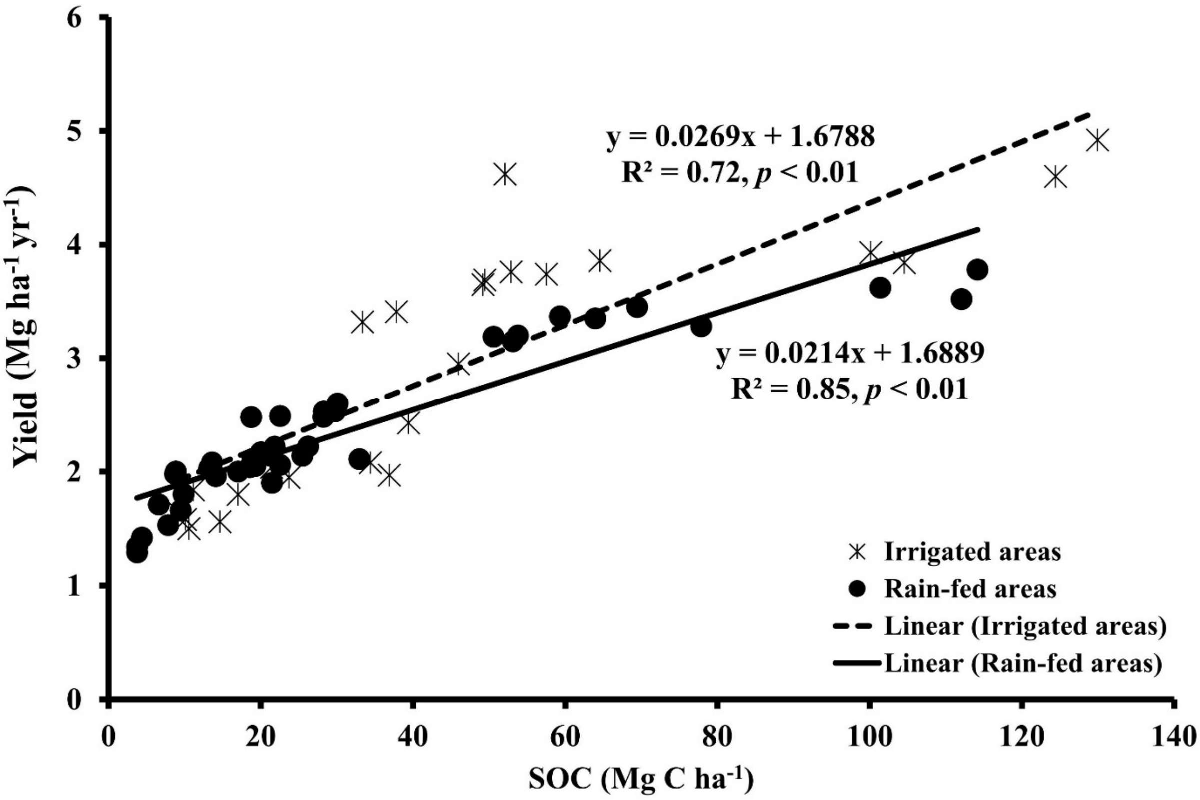


Figure 3-5 Relationship between rice yield and SOC at all sites. The dashed line and solid line were fitted by simple linear regression for irrigated and rain-fed areas, respectively

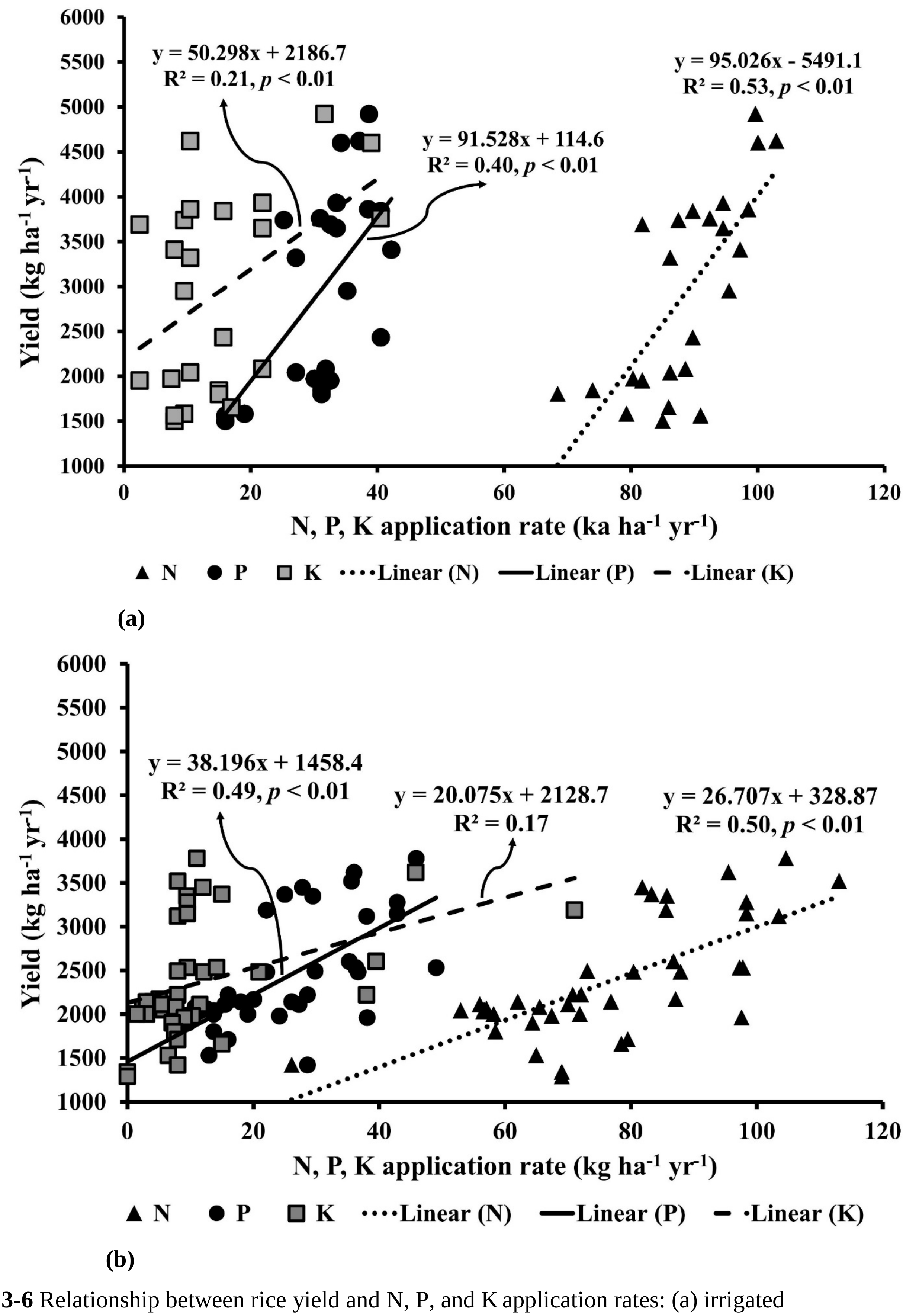
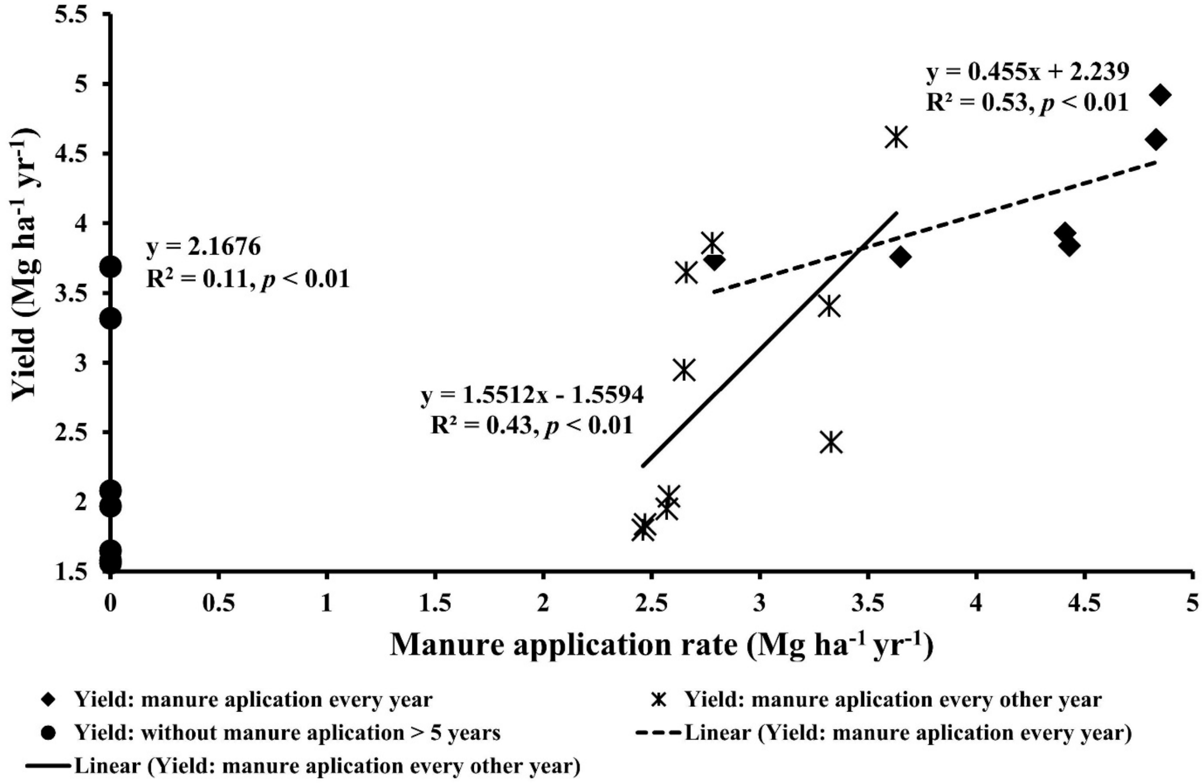
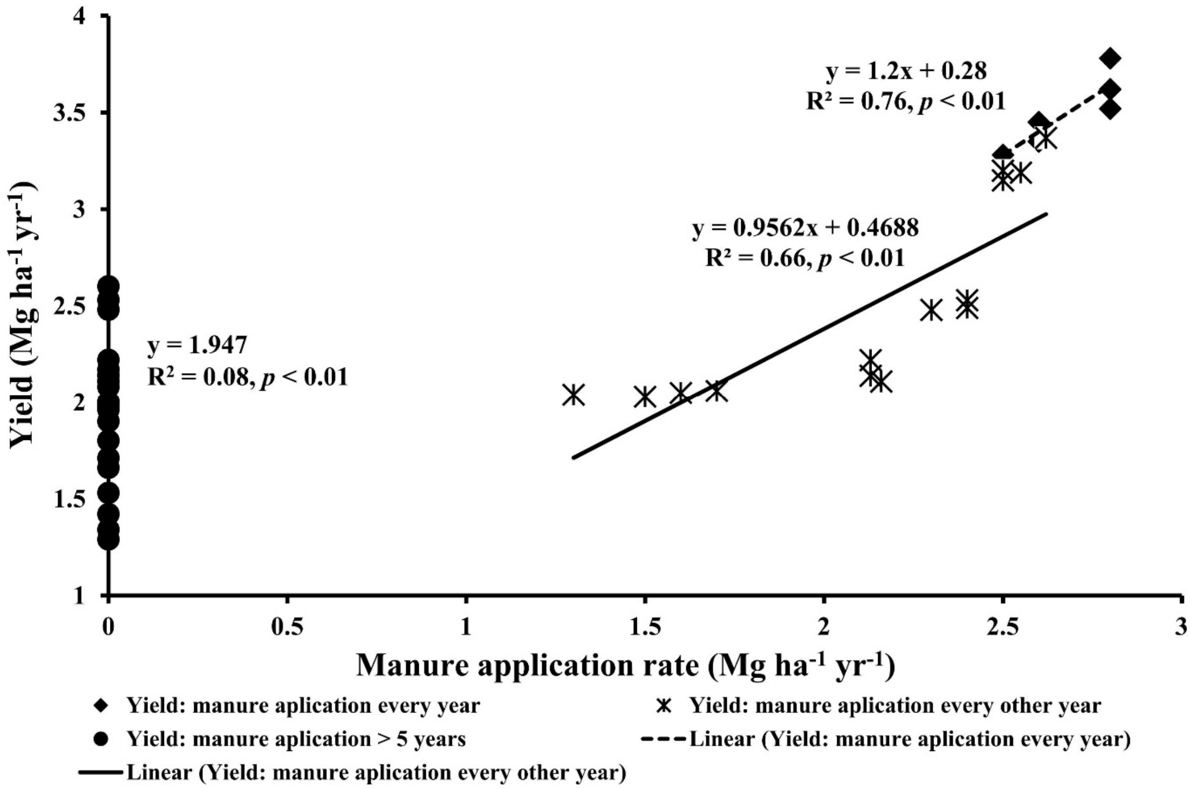


Figure 3-6 Relationship between rice yield and N, P, and K application rates: (a) irrigated areas; (b) rain-fed areas



Yield (Mg ha-1 yr-1)
Manure application rate (Mg ha-1 yr-1)
y = 0.455x + 2.239
R² = 0.53, p < 0.01
y = 2.1676
R² = 0.11, p < 0.01
y = 1.5512x - 1.5594
R² = 0.43, p < 0.01
Yield: manure aplication every year
Yield: manure aplication every other year
Yield: without manure aplication > 5 years
Linear (Yield: manure aplication every year)
Linear (Yield: manure aplication every other year)

(a)



Yield (Mg ha-1 yr-1)
Manure application rate (Mg ha-1 yr-1)
y = 1.2x + 0.28
R² = 0.76, p < 0.01
y = 0.9562x + 0.4688
R² = 0.66, p < 0.01
y = 1.947
R² = 0.08, p < 0.01
Yield: manure aplication every year
Yield: manure aplication every other year
Yield: manure aplication > 5 years
Linear (Yield: manure aplication every year)
Linear (Yield: manure aplication every other year)

(b)

Figure 3-7 Relationship between rice yield and the period of manure application: every year, every other year, and without manure application for more than 5 years: (a) irrigated areas; (b) rain-fed areas

The results of a stepwise multiple regression analysis for SOC and rice yield using manure, N, P, and K fertilizers, taking into consideration the application periods of manure, are shown in Table 3-8. For all sites in irrigated areas, rice yield was significantly correlated with N and P fertilizers, while SOC was significantly correlated with manure. When manure was applied every year, rice yield was significantly correlated with N fertilizer alone, while SOC was significantly correlated with manure alone. When manure application was applied every other year, rice yield was significantly correlated with N and P fertilizers, while SOC was significantly correlated with N fertilizer alone. In cases without manure application for more than 5 years, rice yield was significantly correlated with P fertilizer alone, while SOC was significantly correlated with N, P, and K fertilizers.

For all sites in rain-fed areas, rice yield was significantly correlated with application rates of manure, N and P fertilizers, while SOC was significantly correlated with application rates of manure and N fertilizer. If manure was applied every year, rice yield was significantly correlated with manure application rate only, while SOC was significantly correlated with application rates of manure and N fertilizer. When manure was applied every other year, rice yield and SOC were significantly correlated with N application rate only. If no manure was applied to the field for more than 5 years, rice yield and SOC were significantly correlated with application rates of P.

Table 3-8 Multiple regression equations used to predict SOC and rice yield using manure (M), N fertilizer (N), P fertilizer (P), and K fertilizer (K)

	Rice yield	**SOC**
Irrigated area		
Manure application every year (n = 6)	Rice yield = -4.114 + 0.088(N) (R^2 = 0.805; $p < 0.01$)	SOC = -61.853 + 37.681(M) (R^2 = 0.844; $p < 0.01$)
Manure application every other year (n = 10)	Rice yield = -4.802 + 0.047(N) + 0.101(P) (R^2 = 0.793; $p < 0.01$)	SOC = -80.368 + 1.304(N) (R^2 = 0.670; $p < 0.01$)
Without manure application for more than 5 years (n = 8)	Rice yield = 0.220 + 0.082(P) (R^2 = 0.507; $p < 0.01$)	SOC = -81.413 + 2.101(P) – 0.832(K) + 0.770(N) (R^2 = 0.991; $p < 0.01$)
All sites (n = 24)	Rice yield = -4.875 + 0.074(P) + 0.062(N) (R^2 = 0.669; $p < 0.01$)	SOC = 14.441 + 14.673(M) (R^2 = 0.532; $p < 0.01$)
Rain-fed area		
Manure application every year (n = 6)	Rice yield = 0.280 + 1.200(M) (R^2 = 0.764; $p < 0.01$)	SOC = -257.553 + 92.937(M) + 1.015(N) (R^2 = 0.948; $p < 0.01$)
Manure application every other year (n = 14)	Rice yield = 0.732 + 0.024(N) (R^2 = 0.709; $p < 0.01$)	SOC = -19.838 + 0.681(N) (R^2 = 0.567; $p < 0.01$)
Without manure application for more than 5 years (n = 20)	Rice yield = 1.460 + 0.024(P) (R^2 = 0.522; $p < 0.01$)	SOC = 4.912 + 0.534(P) (R^2 = 0.401; $p < 0.01$)
All sites (n = 40)	Rice yield = 0.762 + 0.305(M) + 0.012(N) + 0.014(P) (R^2 = 0.826; $p < 0.01$)	SOC = -40.917 + 12.531(M) + 0.766(N) (R^2 = 0.683; $p < 0.01$)

3.4 Discussion

3.4.1 Soil characteristics according to farming practices influencing SOC

SOC content is influenced by various regional factors, such as soil type, texture, topography, land use type, and management practices (Hao and Kravchenko, 2007; Wang et al., 2012). Slightly higher SOC was found in the surface soil compared to the subsoil in this study. This might be due to lower of surface litter in the subsoil (Jobbágy and Jackson, 2000). Furthermore, the accumulation of manure on the soil surface enriches SOM in the surface layer (Mathew et al., 2012). This result clearly showed that SOC accumulates in the surface soil, which is a normal phenomenon in tropical soils (Wong et al., 2008; Buol et al., 2011). Soil texture is also an important variable affecting SOC levels, because aggregation processes are favored by small particle sizes that provide high surface areas. Many studies (Konen et al., 2003; Zhao et al., 2006; Zinn et al., 2007; Arevalo et al., 2009; Gami et al., 2009; Schmitter et al., 2010; Chen et al., 2013) have found that SOC is significantly correlated with clay content. However, this study found no significant relationship between clay content and SOC (Table 3-6), while negative correlation between CEC and SOC was found. A few studies were consistent with our findings. For instant, Laopoolkit et al. (2011) found the relationship between SOC and clay is changing from positive in forest to negative in arable land in Northeast Plateau, Thailand. Islam et al. (2014) found the highly negative correlation between CEC with SOC, Northeast Thailand. Furthermore, Hassink (1994) mentioned that the relationship between SOC and sandy soil is unclear, probably because differences in individual soil particles do not create much variation to soil textural classes; consequently, particle size distribution might fail to produce a significant relationship with SOC. This issue suggests that adding manure is more important than soil texture for improving SOC. This hypothesis is supported by Smith and Elliott (1990), who reported that the incorporation of organic materials to soil promotes the aggregation of soil particles. In this study, positive correlations between finer soil particles and SOC (Table 3-6). Thus, SOC increases or decreases in parallel with increasing or decreasing finer soil particles, respectively. Therefore, the fraction of finer soil particles of a given soil type represents an important predictor of SOC in the soil (Parton et al., 1987). Hassink (1996) and Zhao et al. (2006) reported that these trends may be due to the ability of clay and silt particles to absorb organic matter and to protect it from microbial decomposition. ECe was found the positive correlation with SOC. This may be due to the soil samplings were collected in the dry season, and rain-fed areas were mostly covered in this study area. Iwai et al. (2012) reported that ECe increased in the dry season due to the capillary rise of salty groundwater associated with evaporation and low surface cover. On the other hand, ECe decreased in the wet season due to desalinization and salt leaching associated with rainfall infiltration. Soil pH is an important chemical property that is primarily attributed to low rice yield causing low nutrient return by organic materials. Marschner (2011) stated that acidic soils may be limited the use efficiency of N, P, K, Ca, Mg, and Mo, as well as Al and Mn toxicity, which lead to low added nutrients and low crop yields. In the study area, the mean values of soil pH ranged from extremely acidic to slightly acidic in both irrigated and rain-fed areas (Table 3-4). Thus, pH may prevent rice yield and SOC from increasing. Therefore, improved soil management requires a combination of organic and inorganic inputs, particularly manure that are related to C in the soils. Furthermore, fertilizer is required to improve soil fertility.

3.4.2 Effects of pertinent management practices on rice yield and SOC

This study clearly showed that manure and fertilizer application increased crop yield and SOC (Figures 3-6 and 3-7). Other studies have also observed that a combination of manure and chemical fertilizer enhances soil fertility and crop yield (Whitbread et al., 2003; Rasool et al., 2007), and might also benefit SOC sequestration in soil (Shimizu et al., 2015). SOC is higher in paddy soils compared to upland field soils, due to low organic matter decomposition caused by the presence of floodwater in paddy soils (Katoh, 2003). Neue et al. (1997) and a four-year study (1999-2002) by Yang et al. (2005) concluded that increased SOC content in tropical paddy soils is probably caused by increased organic matter inputs and continuous waterlogging. Our results supported this assumption, showing that both SOC and rice yield are correlated with manure application in both irrigated and rain-fed areas (Figure 3-7), with this phenomenon being more pronounced in irrigated areas compared to rain-fed areas (Table 3-7). This result supports the previous study in China, where SOC was found to be higher in paddy soils compared to dry cropland because the anaerobic conditions in flooded soils retain SOC (Pan et al., 2004).

In addition, incorporating green manure is useful to provide N, P, K, and other nutrients to soils (Vityakon et al., 2000). Banger et al. (2009) observed that a sandy soil amended with farmyard manure had 36.1% higher SOC concentrations at 0–15 cm depth compared to soil without any manure. Buysse et al. (2013) showed that application of fresh farmyard manure (30-60 Mg ha^{-1}) to the soil once every 4 or 3 years causes significant increases in SOC (100 ± 50 kg C ha^{-1} yr^{-1}) following a long-term experiment initiated in 1959 at a site in the Hesbaye Region of Belgium. Our results were in line with these studies that the sites where manure was applied every year, leading to higher rice yield and SOC than when manure was applied every other year or without manure application for more than 5 years (Tables 3-1 and 3-2). Our findings also support this phenomenon using the results of multiple regression. The combination of manure and chemical fertilizer was significantly correlated with rice yield and SOC, particularly rain-fed areas (Table 3-8). Thus, enhanced SOC sequestration has a positive effect on rice yield (Figure 3-5). Moreover, our results supported the findings of previous studies showing that the combination of chemical and organic fertilization is the most effective management practice for increasing crop yield and SOC sequestration (Bi et al., 2009; Yan et al., 2013). Lal (2006) computed that every 1 Mg C ha^{-1} increase in the SOC pool could increase rice production by 10–50 kg ha^{-1} yr^{-1}.

However, the rice yield in some irrigated areas was lower than that in rain-fed areas, such as at sites I14, I16, I17, I18, I19 I21, I22, I23, and I24. Two possible explanations exist. First, imbalanced chemical fertilizer application with low P and K were detected at sites, without manure application, such as at sites I16, I17, I21, and I22 (Table 3-1). Second, conventional tillage is the common practice of the farmers in this area, and is finished using a machine in a short period of time. This practice may be lead to inappropriate tillage causing soil degradation (Papendick and Parr, 1997; Bertol et al., 2004) and nutrient depletion by water runoff (Bertol et al., 2007).

In rain-fed areas, Seng et al. (2004) found that, when there was a temporary loss of water in flooded rice systems, straw incorporation increased P availability and uptake, increased soil pH, reduced Al toxicity, increased rice growth, and led to high crop yields. This phenomenon was also detected in this study at sites R12, R13, R14, R15, and R20. These sites had high manure application rates, water runoff was low, there was a temporary dry period, and high rice yield. However, fluctuations in nutrient availability are frequently reported in sandy soils, which have low SOM content and CEC (Haefele et al., 2006; Boling et al., 2008) causing a rapid drop in pH, high Al toxicity, and poor crop responses to fertilizers. This phenomenon occurs because of poor buffering capacities against changes to pH during the drying period (Ragland and Boonpuckdee, 1988). Thus, the management of OM is essential to maintain CEC (Linquist et al., 2007).

3.4.3 Recommendation for suitable rice cultivation practices

This investigation showed that a combination of manure along with balanced N, P, and K fertilizer application, increases SOC due to soil organic material can be mineralized towards releasing the nutrient, which subsequently can be taken up by crops to increase crop yields. Thus, SOC is an important factor for determining crop yields. Site-specific management practice recommendations can be implemented as the multiple regression equations in Table 3-8, which indicated the key factors affecting rice yield and SOC. In irrigated area, to sustain rice yield, when manure is available every year or every other year, N and P fertilizers should be practiced due to manure application can act as a source of nutrients (Manna et al., 2007). When manure is not applied at all for more than 5 years, only P fertilizers should be applied. In rain-fed area, when manure application is available every year, applying manure alone can obtain the expected rice yield. In case of manure is available every other year, only N fertilizer should be applied. When manure is not applied at all for more than 5 years, P fertilizers should be used. More importantly, optimal N, P, and K fertilizer application rates and rehabilitation of irrigation infrastructure require immediate focus because they are major factors that increase rice yield and SOC.

3.5 Conclusions

This study recorded significant differences were found in rice yield and SOC between irrigated and rain-fed areas. There were significant positive correlations between rice yield and manure and fertilizer application rates, but there was no significant correlation between SOC and clay content. To increase the average rice yield and SOC, a combination of high manure and fertilizer application rates should be implemented, representing a sustainably beneficial practice for both areas. The results of our study show that SOC and rice yield may be enhanced through the selection of the optimal N, P and K fertilizer application rates, in parallel to increasing irrigation in Thailand.

Chapter 4

Practices for reducing greenhouse gas emissions from rice production in tropical monsoon areas

4.1 Introduction

Rice fields have been a concern of scientists worldwide where the three most important greenhouse gases (GHGs) are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Zheng et al., 2004; Li et al., 2005) because of their positive increases in radiative forcing, and they are the most potent long-lived GHGs contributing to global warming (IPCC, 2007). Flooded rice fields emit CH_4 due to a methanogenesis process that occurs in anaerobic conditions during which organic matter (OM) undergoes decomposition (Jain et al., 2004). Factors affecting CH_4 emissions, such as weather conditions (van Hulzen et al., 1999), water regime (Kang et al., 2002), soil properties (Mitra et al., 2002), land practices, i.e., irrigation (Lu et al., 2000), organic amendments (Adhya et al., 2000), fertilization (Hou et al., 2000), and rice varieties (Mitra et al., 1999), have been considered. Most N_2O emissions occur from nitrogen (N) fertilizer application (Liao and Yan, 2011), for which the N application rate is the main driver of N_2O production for either wet or dry soil (Qin et al., 2010). However, rain-fed areas are more comparable and have stronger N_2O emissions from rice fields than other areas do (Hou et al., 2012) because of changes in soil oxygen status, soil redox potential, soil moisture, and soil temperature (Peng et al., 2011). With regard to CO_2 emissions, the main sources are the activities of farmers on their land, particularly when crop residues are burned and machines use energy either for cropping operations (i.e., tillage, harvesting, and so on) or stationary operations (i.e., water pumping, land preparation, and application of pesticides and herbicides) (Lal, 2004a). Furthermore, the burning of crop residues not only emits CO_2, but also is a major source of gaseous pollutants such as carbon monoxide (CO), CH_4, N_2O, and hydrocarbons in the troposphere (Crutzen et al., 1990). However, soils have the potential to mitigate increasing CO_2 concentrations through carbon (C) sequestration, with the maximum potential global sequestration varying from 0.45 to 0.9 Pg C yr^{-1} (Lal, 2004b). Therefore, understanding the effects of management practices on GHG emissions and SOC is necessary to improve management practices to reduce GHG emissions from rice fields.

Thailand's rice production area is 13.28 million ha, which is approximately 55.6% of the country's total agricultural area (Liese et al., 2014). Geographically, Thailand is divided into four main regions: the North, Northeast, Central, and South. Rice is grown throughout the country, but the Northeast, North, and Central are the most important rice growing regions with 49.1, 25.4, and 22.3%, respectively, of the country's total rice growing area. The Northeast has a majority of the rain-fed lowland areas with around 4.8 million ha (Jongdee et al., 2006) and shallow drought-prone areas (Khush, 1984). Traditional rice varieties, particularly Jasmine or Khao Dawk Mali 105 (KDML 105), are grown in the Northeast. Although the rice quality is high, the rice yield is low, and the farmers in this area are the poorest compared to the other regions (Liese et al., 2014). To obtain sustainable management of the sandy soil in this area, it is necessary to understand the land management practices, which include the farmers' actual activities and practices, and determine the appropriate practices in terms of the soil characteristics and farmers' capability. By understanding these elements, the pros and cons of each land management practice in relation to GHG emissions, SOC, and rice yield can be estimated thoroughly. To estimate these overall effects in rice fields, the concept of net global warming potential (GWP) was proposed based on the radiative properties of CO_2, CH_4, and N_2O emissions and SOC variations, expressed as kg CO_2eq ha^{-1} yr^{-1} (Robertson and Grace, 2004). Moreover, the agricultural practices can be related to GWP by estimating net GWP per ton of crop yield, which is referred to as greenhouse gas intensity (GHGI) (Mosier et al., 2006). Net GWP reflects the balance between SOC storage and GHG emissions. A negative net GWP value means that the system is taking GHGs out of the atmosphere, whereas a positive net GWP value means that GHGs are being added to the atmosphere and net GWP increases (Robertson et al., 2000). In addition, a positive GHGI value indicates a net source of GHGs per kilogram of yield per year, whereas a negative value indicates a net sink of GHGs in soil (Shang et al., 2011). No studies to date have estimated net GWP and GHGI in this area under different land management practices, including irrigated versus rain-fed fields. The aim of this study was to estimate the effect of land management practices on net GWP and GHGI.

4.2 Materials and methods

4.2.1 Description of the study area

The study area is situated in Thung Kula subdistrict, Suwannaphum district, Roi-Et province, Thailand (15º 28′ N, 103º 48′ E) and covers 59.45 ha, 22.29 ha and 37.16 ha of which was irrigated and rain-fed, respectively. According to the survey of soil nutrient status in Thailand from 2004–2008, 72,484 soil nutrient testing results of 13 sites in the study area (i.e., pH, OM, organic carbon (OC), total nitrogen, available P, available K, electrical conductivity, and lime requirement) were collected by the laboratory of the Office of Science for Land Development, Land Development Department, Ministry of Agriculture and Cooperatives, Thailand. Data from the 13 sites, 9 of which were irrigated areas and 4 in rain-fed areas, in Thung Kula subdistrict were collected and the SOC was estimated in 2004. Soil samples from the same 13 study sites were collected again in 2014 to estimate the soil organic carbon sequestration rate (SOCSR) from 2004 to 2014.

4.2.2 Data collection

The data were obtained over a 5 year period (2010–2014). Questionnaires were conducted at each sampling site to record the crop and management practices by farm owners. At 13 sites, 13 farms provided crop and land management data. Rice yields and management practice data (i.e., dates of planting and harvesting; rates of application of fertilizers, manure, pesticides, and irrigation; and field operations performed) were collected from the questionnaire survey in 2014 and from the record book for the standards for good agricultural practices (GAP) of farm owners over the 5 year study period (2010–2014). The record books were disseminated to the farmers by the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand to record their agricultural activities, which helped this study to obtain precise data on operational practices.

4.2.3 Soil sampling

Soil samples were collected during the dry season after the rice harvest (November, 2014). At each site, the soil horizons from 0 to 40 cm depth were identified by considering specific physical features; namely, color and texture. Any visible roots, stones, or organic residues were removed manually after the samples were air dried at room temperature (31-33°C). Then, the samples were passed through a 2-mm sieve. The SOC content was determined using the wet oxidation method with $K_2Cr_2O_7$ and concentrated H_2SO_4 as described by Walkley and Black (1934). After a 24-hr drying period in an oven at 105 °C, soil bulk density was determined as the dry weight per unit volume of the soil core.

4.2.4 Estimation of GHG emissions

The GHG emissions were calculated within the farm gate. Therefore, the GHG emissions of raw materials production and the transportation of agricultural inputs to the farm were not included. The emission factors for the calculation of GHG emissions are presented in Table 4-1.

4.2.4.1 CH_4 emissions from rice production

Field CH_4 emissions from rice cultivation were used as the model for the calculations according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). The baseline emission factor was taken from Yan et al. (2003), who adjusted the region-specific emission factors for rice fields in east, southeast and south Asian countries, and all scaling factors used were from the IPCC (2006). The basic equation to estimate CH_4 emissions from rice cultivation are presented in Equation (1) to (3). CH_4 emissions were estimated by multiplying the daily emissions factor by the cultivation period of rice and harvested area.

$$CH_4 = EF \times t \tag{1}$$

where CH_4 is the methane emissions from rice cultivation (kg CH_4 ha^{-1}), EF is the adjusted daily emissions factor (kg CH_4 ha^{-1} day^{-1}), and t is the cultivation period of rice (days)

Emissions from each different region were considered by multiplying a baseline default emissions factor by the various scaling factors as shown in Equation (2).

$$EF = (EF_c \times SF_w \times SF_p \times SF_o \times SF_{s,r}) \tag{2}$$

where EF is the adjusted daily emissions factor for a particular harvested area, EF_c is the baseline emissions factor for continuously flooded fields without organic amendments, SF_w is the scaling factor to account for the differences in water regime during the cultivation period, SF_p is the scaling factor to account for the differences in water regime in the season before the cultivation period, SF_0 is the scaling factor that accounts for differences in both type and amount of organic amendment applied source, and $SF_{s,r}$ is the scaling factor for soil type, rice cultivar, etc. (Neglected in this study)

Meanwhile, Equation (3) and the default conversion factor for farmyard manure presented an approach to vary the scaling factor according to the amount of farmyard manure applied.

$$SF_0 = (1 + \sum_i ROA_i \times CFOA_i)^{0.59} \quad (3)$$

where ROA_i is the application rate of organic amendment *i* in dry weight for straw and fresh weight for others in ton ha^{-1}, and $CFOA_i$ is the conversion factor for organic amendment *i* in terms of its relative effect with respect to straw applied shortly before cultivation.

4.2.4.2 N_2O emissions from managed soils

The methodology for estimating direct N_2O emissions from chemical N fertilizer application is given by IPCC Guidelines (2006) (Tier 1) as follows:

$$Direct\ N_2O\ emissions = [F_{SN} \times EF_1 + (F_{SN})_{FR} \times EF_{1FR}] \times 44/28 \quad (4)$$

where F_{SN} and $(F_{SN})_{FR}$ are the annual amount of synthetic fertilizer N applied to dry land and rice fields, respectively, and EF_1 and EF_{1FR} are the emissions factors of N_2O caused by fertilizer N input in dry land and rice fields, respectively.

The calculation formula for indirect N_2O emissions caused by chemical N fertilizer application is listed below:

$$Indirect\ N_2O\ emissions = [F_{SN} \times Frac_{GASF} \times EF_2 + F_{SN} \times Frac_{LEACH-(H)} \times EF_3] \times 44/28 \quad (5)$$

where $Frac_{GASF}$ is the fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_X, EF_2 is the emissions factor for N_2O emissions from atmospheric deposition of N on soil and water surfaces, $Frac_{LEACH-(H)}$ is the fraction of all N which is lost when added to/mineralized in managed soil in regions where leaching/runoff occurs, and EF_3 is the emissions factor for N_2O emissions from N leaching and runoff.

4.2.4.3 CO_2 emissions from fossil fuel utilization

The CO_2 emissions for the diesel and gasoline usage of stationary combustion were also taken from the IPCC (2006). Meanwhile, CO_2 emissions from the mobile combustion of the diesel fuel of farm tractors and harvesters were estimated from the emission factors of Maciel et al. (2015), and CO_2 emissions from gasoline fuel were estimated from the EPA (2014).

2.4.3.1 Diesel fuel

CO_2 emissions from diesel fuel utilization = Total amount of diesel fuel × emissions factor of diesel fuel combustion (6)

2.4.3.2 Gasoline fuel

CO_2 emissions from gasoline fuel utilization = Total amount of gasoline fuel × emissions factor of gasoline fuel combustion (7)

4.2.4.4 CO_2 emissions from insecticides and herbicides utilization

Figures for insecticides and herbicides were provided by the emissions factors from Lal (2004c).

CO_2 emissions from insecticides and herbicide utilization = Total amount of insecticides and herbicide application × emissions factor of insecticides and herbicide utilization (8)

4.2.4.5 GHG emissions from field burning

The calculation for GHG emissions from field burning was calculated as follows:

The quantity of rice straw = Rice production × Residue to crop ratio (9)

Amount of burned residues = Quantity of rice straw × fraction of area burned × dry matter fraction × fraction burned × fraction oxidized (10)

CH_4 emissions from field burning = Amount of burned residues × CH_4 emissions factor (11)

N_2O emissions from field burning = Amount of burned residues × N_2O emissions factor (12)

where fraction of area burned is proportion of rice straw subject to open field burning, which is based on the field survey (fraction of area burned = 1 for rice straw in the whole area was burned). The amount of burned residue was estimated “0” if no burning rice straw.

Table 4-1 Emissions factors used for the calculation of GHG emissions within the farm gate (utilization phase) (Arunrat et al., 2016)

Activity	Emissions factor	Unit	Source
Agriculture input			
Diesel used (stationary combustion) for farm operation	2.7446	kg CO_2eq L^{-1}	IPCC (2006)
Gasoline used (stationary combustion) for farm operation	2.1896	kg CO_2eq L^{-1}	
Diesel used (mobile combustion) for farm operation	Tractor = 3.908	kg CO_2eq L^{-1}	Maciel et al., (2015) (calculated with diesel density of 0.832 kg L^{-1})
	Harvester = 2.645		
Gasoline used (mobile combustion) for farm operation	2.319	kg CO_2eq L^{-1}	EPA (2014)
Insecticide	5.1	kg CO_2eq kg^{-1}	Lal (2004c)
Herbicide	6.3	kg CO_2eq kg^{-1}	Lal (2004c)
CH_4 emission from rice cultivation			
EF_c	3.12	kg_{CH4} ha^{-1} day^{-1}	Yan et al., (2003)
SF_w	0.52 in all systems		IPCC (2006)
SF_p	*Rw* = 0.68, *Lw*, *Ld* = 1		
ROA_i	2.5	ton ha^{-1}	
$CFOA_i$	*Rw* = 0.29, *Lw*, *Ld* = 1		
SF_0	*Rw* = 1.4, *Lw*, *Ld* = 2.1		

Direct and Indirect N_2O emission from managed soils (chemical and organic fertilizer)			
EF_1	0.01	kg N_2O-N kg^{-1} N input	IPCC (2006)
EF_{1FR}	0.003	kg N_2O-N kg^{-1}N input	
EF_2	0.01	kg N_2O-N (kg NH_3-N + kg NO_x-N volatilized)$^{-1}$	
EF_3	0.0075	kg N_2O-N kg leaching per runoff	
$Frac_{GASF}$	0.1	kg NH_3-N + NO_x-N kg^{-1} N applied	
$Frac_{LEACH-(H)}$	0.3	kg N kg^{-1} N additions	
Burning crop residue			
CH_4	2.7	g kg^{-1} dry matter burned	IPCC (2006)
N_2O	0.07	g kg^{-1} dry matter burned	
Dry matter fraction	1		
Fraction burn	0.29		
Fraction oxidized	0.9		
Rice residue to crop ratio	Irrigated areas: major rice = 1.06; second rice = 0.65		Kanokkanjana and Garivait (2013)
	Rain-fed areas: major rice and second rice = 0.55		

4.2.5 SOC calculation

SOC stock was calculated by:

$$SOC = (BD \times OC \times D) \times 100 \quad (13)$$

where SOC is soil organic carbon stock (kg C ha^{-1}), BD is soil bulk density (kg m^{-3}), OC is organic carbon content (%), and D is soil sampling depth (m).

The soil organic carbon sequestration rate (SOCSR) was calculated as follows:

$$SOCSR \text{ (kg C ha}^{-1}\text{ yr}^{-1}) = (SOC_t - SOC_0) / 10 \quad (14)$$

where SOC_t and SOC_0 are the SOC contents measured in 2014 and 2004, respectively (kg C ha^{-1}), and 10 is the number of years from 2004 to 2014.

4.2.6 Net global warming potential

The global warming potential (GWP) based on the CH_4, CO_2, and N_2O emissions was used to account for the climatic impact on rice yield under different land management practices. To assess the combined GWP, CH_4 and N_2O were calculated as CO_2 equivalents over a 100-year time scale using a radiative forcing potential relative to CO_2 of 28 for CH_4 and 265 for N_2O (IPCC, 2013). The net GWP of a rice field equals the total CO_2 emissions equivalents minus the SOCSR in the rice field (Liu et al., 2015; Zhang et al., 2015):

$$Net\ GWP = (CO_2\ emissions \times 1) + (N_2O\ emissions \times 265) + (CH_4\ emissions \times 28) - (SOCSR \times 44/12) \quad (15)$$

4.2.7 Greenhouse gas intensity

The GHGI is calculated as a ratio of net GWP and rice yield, as described in Shang et al. (2011):

$$GHGI = net\ GWP/rice\ yield \tag{16}$$

4.2.8 Statistical analysis

Statistical analyses of the data were carried out using SPSS (Version 20.0, USA). The mean and standard deviation (SD) values were used to represent rice yield, SOC, emissions of CO_2, N_2O and CH_4, GWP, SOCSR, net GWP and GHGI in each site. Differences in rice yield, SOC, emissions of CO_2, N_2O and CH_4, GWP, SOCSR, net GWP and GHGI between irrigated and rain-fed areas were analyzed with t-test and least significant difference (LSD) test ($p < 0.05$). Simple linear regression analysis was used to find the relationship between two variables by fitting a linear equation. Stepwise multiple regression analysis was conducted to evaluate the relationships of rice yield and SOCSR with the pertinent management practice. Pearson's correlation analysis was conducted to evaluate the relationships among the GHG emissions and pertinent factors.

4.3 Results

4.3.1 Pertinent management practices, rice yield, and SOC

There were no significant differences in the manure and fertilizer application rates, the amount of burned rice residues, rice yield, and SOC between irrigated and rain-fed areas (Table 4-2). The manure application rate varied across sites, from 0 to 4830 $kg \cdot ha^{-1} \cdot year^{-1}$, with averages of 2864 and 1888 $kg \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. The N fertilizer application rate ranged from 38 to 98 $kg \cdot ha^{-1} \cdot year^{-1}$ across sites, with averages of 72 and 56 $kg \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. The P_2O_5 and K_2O application rate ranged from 14 to 46 and 6 to 46 $kg \cdot ha^{-1} \cdot year^{-1}$ across sites for irrigated and rain-fed areas, respectively. The average P_2O_5 and K_2O application rates were 27 and 22 $kg \cdot ha^{-1} \cdot year^{-1}$ for irrigated areas and 26 and 15 $kg \cdot ha^{-1} \cdot year^{-1}$ for rain-fed areas. Meanwhile, the amount of burned rice residue was also variable, ranging from 0 to 593 kg·ha^{-1}·year^{-1}, with averages of 263 and 148 kg·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively.

The average rice yield, SOC_t, SOC_0, and SOCSR were 3,307 kg·ha^{-1}·year^{-1}, 53,884 kg·C·ha^{-1}, 42,151 kg·C·ha^{-1}, and 1,173 kg·C·ha^{-1}·year^{-1} (Table 4-2) respectively. There was a significant correlation between rice yield and SOC_t ($R^2 = 0.51$, $p < 0.01$), SOC_0 ($R^2 = 0.46$, $p < 0.01$) (Figure 4-1), and SOCSR ($R^2 = 0.52$, $p < 0.01$) (Figure 4-2). Although, the manure, N, P_2O_5, and K_2O fertilizer applications were the major underlying factors for increasing rice yield, they were exiguously correlated positively with rice yield ($R^2 = 0.16$, $p > 0.01$, $R^2 = 0.11$, $p > 0.01$, $R^2 = 0.46$, $p > 0.01$, and $R^2 = 0.69$, $p > 0.01$ respectively) (Figure 4-3(a), (b)). On the other hand, the amount of burned rice residues showed a negative correlation to rice yield ($R^2 = 0.02$, $p > 0.01$) (Figure 4-3(c)). In addition, rice yield and SOCSR was related markedly to only the amount of K_2O fertilizer application rates (Table 4-3).

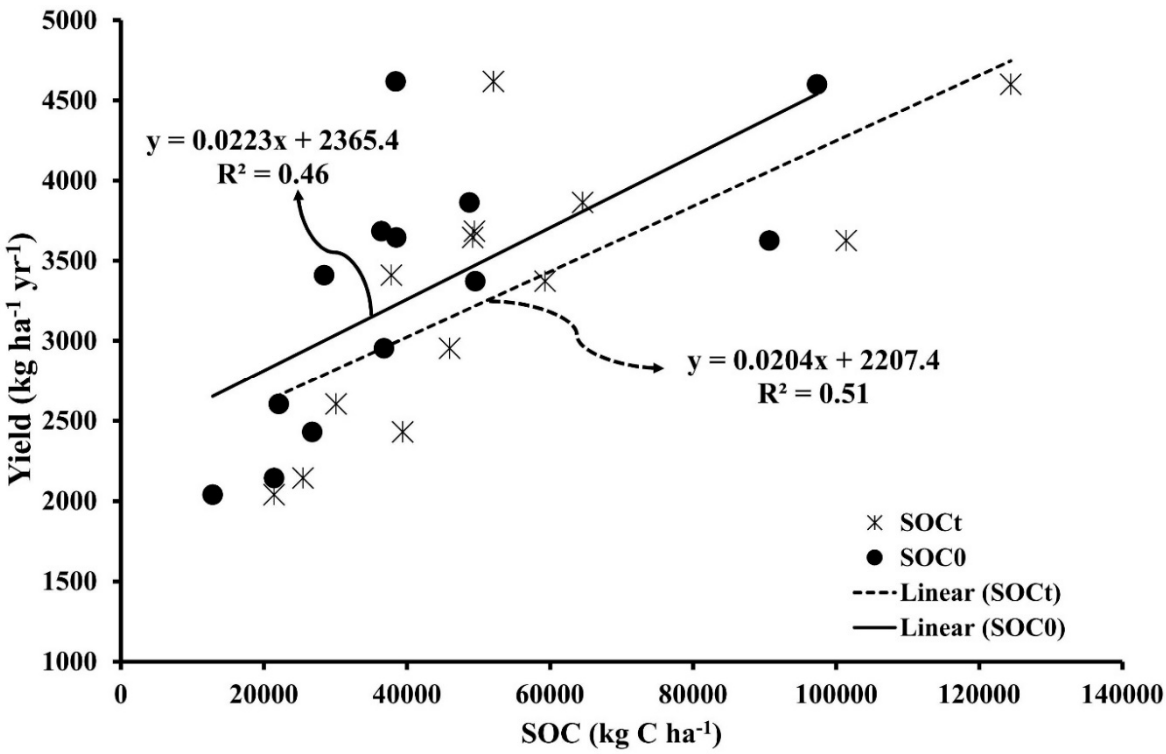


Figure 4-1 Relationship between rice yield and SOC_t and SOC_0 for all sites

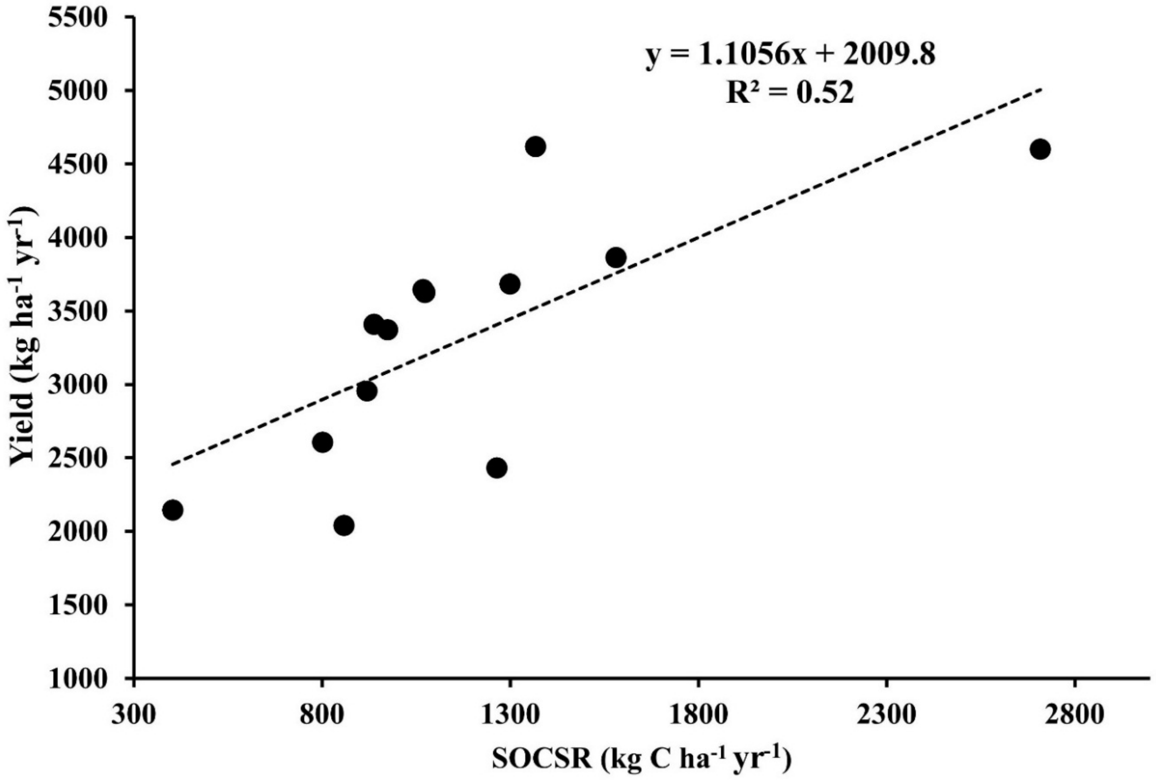
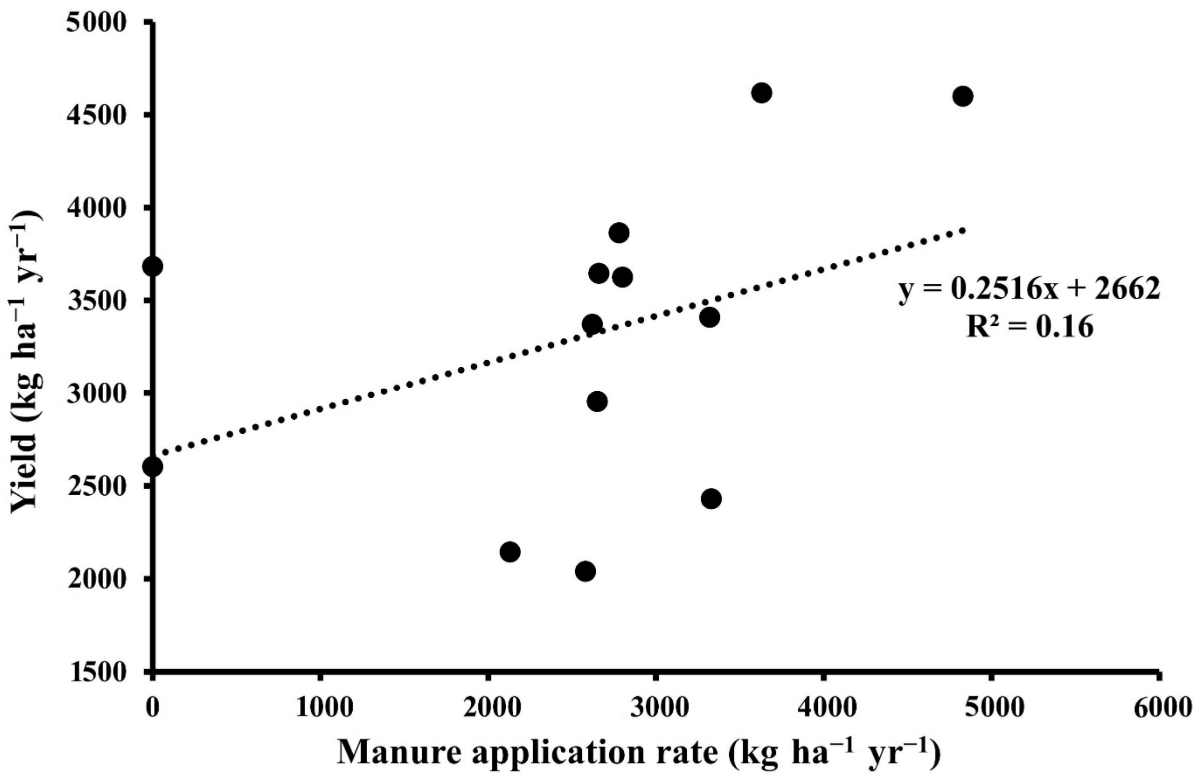
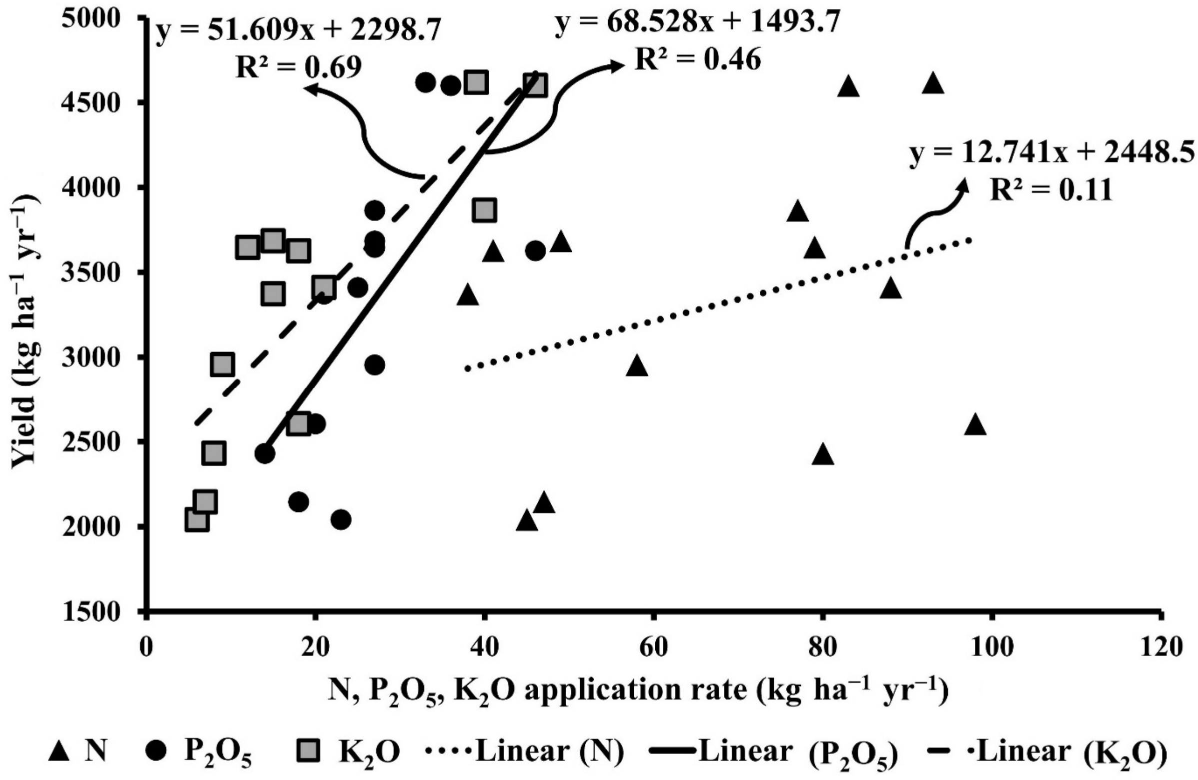


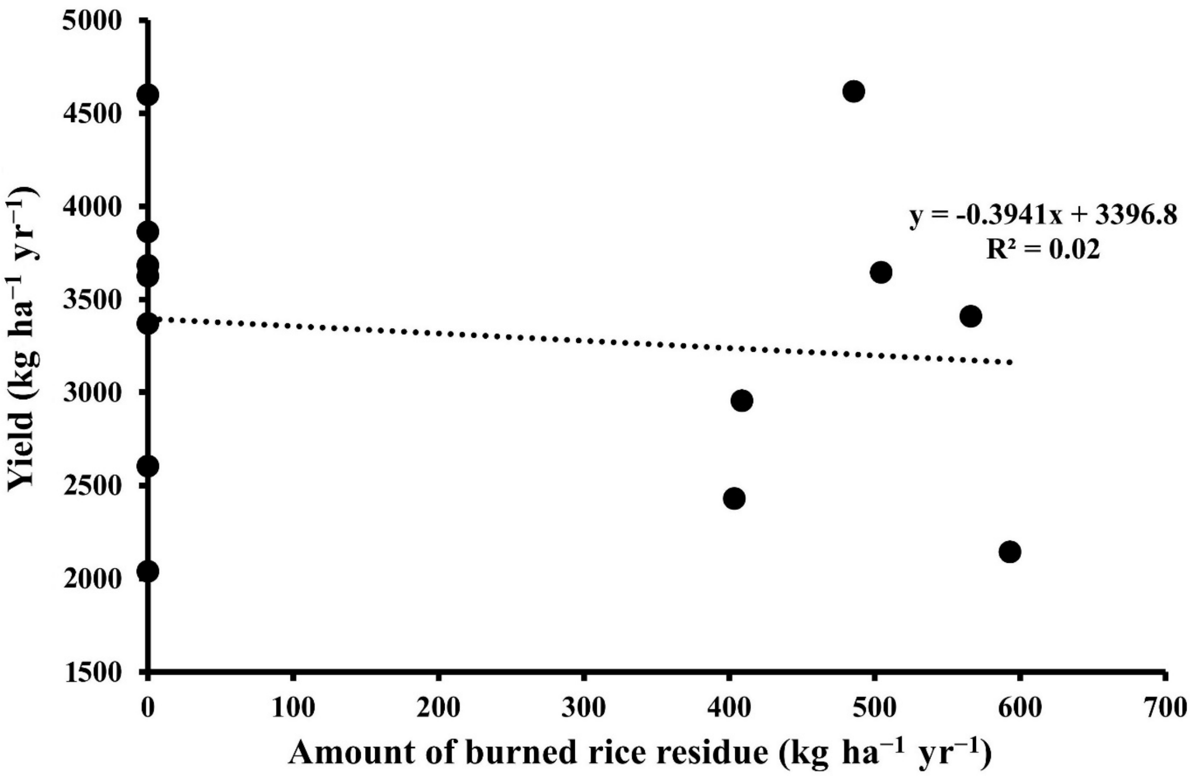
Figure 4-2 Relationship between rice yield and SOCSR for all sites



(a)



(b)



(c)

Figure 4-3 Relationship between pertinent practices and rice yield: (a) manure application, (b) fertilizer application, and (c) amount of burned rice residue

Table 4-2 Pertinent management practices, rice yield, and SOCSR (Mean ± SD)

Site No.	Manure application rate (kg ha^{-1} yr^{-1})	Fertilizer application rate (kg ha^{-1} yr^{-1})			Burned rice residue (kg ha^{-1} yr^{-1})	Rice yield (kg ha^{-1} yr^{-1})	SOC_t (kg C ha^{-1})	SOC_0 (kg C ha^{-1})	SOCSR (kg C ha^{-1} yr^{-1})
		N	P_2O_5	K_2O					
I1	3320	88	25	21	566	3410	37810	28430	938
I2	4830	83	36	46	0	4600	124400	97320	2708
I3	2780	77	27	40	0	3864	64540	48730	1581
I4	0	49	27	15	0	3684	49430	36440	1299
I5	3630	93	33	39	485	4618	52100	38430	1367
I6	3330	80	14	8	403	2430	39400	26760	1264
I7	2660	79	27	12	504	3646	49180	38500	1068
I8	2580	45	23	6	0	2040	21430	12850	858
I9	2650	58	27	9	409	2954	45960	36770	919
Average	2864 ± 1287	72 ± 17	27 ± 6	22 ± 16	263 ± 254	3472 ± 882	53806 ± 28973	40470 ± 23542	1334 ± 568
R1	2800	41	46	18	0	3626	101390	90660	1073
R2	2620	38	21	15	0	3372	59290	49550	974
R3	2130	47	18	7	593	2144	25460	21430	403
R4	0	98	20	18	0	2604	30100	22090	801
Average	1888 ± 1290	56 ± 28	26 ± 13	15 ± 5	148 ± 297	2937 ± 684	54060 ± 34926	45933 ± 32570	813 ± 295
p-value	0.233	0.217	0.954	0.238	0.838	0.308	0.989	0.736	0.116
Overall	2564 ± 1319	67 ± 22	26 ± 8	20 ± 14	228 ± 261	3307 ± 838	53884 ± 29404	42151 ± 25330	1173 ± 547

I = Irrigated area, R = Rain-fed area, *p*-value indicates a significant difference of value between irrigated and rain fed areas

Table 4-3 Multiple regression equations to predict rice yield and SOCSR using manure (M), N fertilizer (N), P_2O_5 fertilizer (P), K_2O fertilizer (K), and burned rice residues (B)

Depended Variable	Equation
Rice yield	Yield = 51.61 × K + 2298.72 (R^2 = 0.66, $p < 0.05$)
SOCSR	SOCSR = 31.91 × K + 549.84 (R^2 = 0.59, $p < 0.05$)

4.3.2 CO_2 emissions

In this study, CO_2 emissions reflected the utilization of fossil fuels (diesel and gasoline), insecticides, and herbicides. The utilization of diesel and gasoline fuels revealed that rain-fed areas generated more CO_2 emissions from drainage water into the field than the irrigated areas. Moreover, at the sites where there was no burning rice residue (sites I2, I3, I4, I8, R1, R2, and R4) there was a slightly higher amount of CO_2 emissions from utilization of diesel fuel than burned rice residue sites (sites I1, I5, I6, I7, I9, and R3). This is because farmers need to use the machine for the incorporation of rice residues into the soil but not for burning rice residues. The CO_2 emissions from the utilization of diesel fuel ranged from 127 to 211 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ across sites, with averages of 152 and 188 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. Gasoline fuel utilization generated CO_2 emissions, varying from 10 to 73 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ in all sites, with averages of 30 and 51 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. Meanwhile, CO_2 emissions from the utilization of insecticides and herbicides ranged from 37 to 73 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ across sites, with averages of 52 and 43 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. There were significant differences for the utilization of diesel fuel ($p < 0.05$), while there were no significant differences in the utilization of gasoline fuel, or insecticides and herbicides, between irrigated and rain-fed areas ($p < 0.05$) (Table 4-4).

The total CO_2 emissions were estimated, ranging from 201 to 301 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ across sites, with averages of 233 and 281 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively (Table 4-5). The land management practice of the high amount of diesel fuel utilization caused the highest total CO_2 emissions as seen at site R1, which was the highest amount of diesel fuel utilization at 211 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ compared with others (Table 4-4).

4.3.3 N_2O emissions

Remarkably, N_2O emissions depended on chemical fertilizer application and the amount of burned rice residues. N_2O emissions from chemical fertilizer utilization ranged from 211 to 541 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ in all sites, with averages of 409 and 346 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. Irrigated areas had slightly higher N_2O emissions from chemical fertilizer utilization than the rain-fed areas, but there were no significant differences between both areas ($p < 0.05$). Meanwhile, N_2O emissions from burning rice residue were found the wide range of 0 to 11 kg·CO_2eq·ha^{-1}·year^{-1} in all sites, with averages of 5 and 3 kg·CO_2eq·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively, and there were no significant differences between both areas ($p < 0.05$) (Table 4-4).

A range of total N_2O emissions values (211–541 kg·CO_2eq·ha^{-1}·year^{-1}) was calculated, with averages of 414 and 349 kg·CO_2eq·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively (Table 4-5). Highly positive correlations were found between N_2O emissions and N fertilizer application, with r values of 0.925 ($p < 0.01$) (Table 4-6). The highest total N_2O emissions were found at site R4, where the high amount of chemical was practiced. On the other hand, at site R2, where the lowest amount of chemical fertilizer was found and there was no use of burned rice residues (Table 4-2), the lowest total N_2O emissions were seen.

4.3.4 CH_4 emissions

Manure application, the amount of burned rice residues, and the length of rice cultivation affected the CH_4 emissions. CH_4 emissions from rice cultivation ranged from 794 to 5518 kg·CO_2eq·ha^{-1}·year^{-1} across sites, with averages of 4359 and 1905 kg·CO_2eq·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively. There were significant differences for CH_4 emissions from rice cultivation between irrigated and rain-fed areas ($p < 0.05$). Irrigated areas had obviously higher CH_4 emissions from rice cultivation than rain-fed areas. In addition, CH_4 emissions from burning rice residue had the wide range of 0 to 45 kg·CO_2eq·ha^{-1}·year^{-1} in all sites, with averages of 20 and 11 kg·CO_2eq·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively, but there were no significant differences between both areas ($p < 0.05$) (Table 4-4).

The range of total CH_4 emissions was broad, varying from 794 to 5556 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$. The average value was 3621 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ in all sites (Table 4-5). Highly positive correlations were found between CH_4 emissions and manure application, GWP, net GWP, and GHGI, with r values of 0.739 ($p < 0.01$), 0.997 ($p < 0.01$), 0.932 ($p < 0.01$), and 0.604 ($p < 0.05$), respectively (Table 4-6). These correlations may reflect that the land management practice of applying large amounts of manure or burned rice residues, and the long rice cultivation length, would generate high CH_4 emissions. The highest and lowest CH_4 emissions were seen at site I7 and R4, respectively (Table 4-5).

4.3.5 SOCSR

The SOCSR in this study varied across sites from 403 to 2708 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$, with averages of 1334 and 813 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ for irrigated and rain-fed areas, respectively. The average value for all sites was 1173 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$ (Table 4-5). The SOCSR had a highly positive correlation with rice yield ($r = 0.722$, $p < 0.01$) and K_2O fertilizer application ($r = 0.787$, $p < 0.01$), whereas a negative correlation was found with the amount of burned rice residues and GHGI, but was not statistically significant (Table 4-6). The results were obvious at sites I2 and R1, where the manure application was high and no burned rice residues were used. Therefore, these sites achieved high SOCSR and rice yield. However, it seems that not only can manure application and a lack of burned rice residues increase SOCSR and rice yield, but high chemical fertilizer application also can (Table 4-2).

4.3.6 Net GWP and GHGI

The evaluation of net GWP and GHGI under different land management practices is shown in Table 4-5. The net GWP varied across sites, ranging from 819 to 5170 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$, with an average value of 3090 $kg \cdot CO_2eq \cdot ha^{-1} \cdot year^{-1}$, and GHGI ranged from 0.31 to 1.68 $kg \cdot CO_2eq \cdot kg^{-1}$ yield, with an average value of 0.97 $kg \cdot CO_2eq \cdot kg^{-1}$ yield. The net GWP showed a highly positive correlation with manure application, amount of burned rice residue, CH_4 emission, GWP, and GHGI (r = 0.609 ($p < 0.05$), 0.555 ($p < 0.05$), 0.932 ($p < 0.01$), 0.936 ($p < 0.01$), and 0.778 ($p < 0.01$), respectively). Meanwhile, GHGI had a positive correlation with the amount of burned rice residue, CH_4 emission, GWP, and net GWP, with r values of 0.656 ($p < 0.05$), 0.604 ($p < 0.05$), 0.595 ($p < 0.05$), and 0.778 ($p < 0.01$), respectively. However, this study found a negative correlation of net GWP and GHGI with CO_2 emissions ($r = -0.640$ ($p < 0.05$), and −0.662 ($p < 0.05$), respectively). This is because the sites with high net GWP and GHGI in this study generated a low amount of CO_2 emissions, but emitted a high amount of N_2O emissions from chemical fertilizer application.

Multiple regression equations to predict GHGI using manure, N, P_2O_5 and K_2O fertilizers, and burned rice residues showed that GHGI = 0.001 × burned rice residues + 0.74 ($R^2 = 0.36$, $p < 0.01$). This finding revealed that burned rice residue was the main factor determining the GHGI in this area. In addition, land management practices where the net GWP and GHGI were low involved no burned rice residues, incorporation of manure and chemical fertilizer, or application of chemical fertilizers at sites R1, R2, and R4, respectively. Meanwhile, similar land management practices had a high net GWP and GHGI as seen at sites I2, I3, I4, and I8 (Table 4-5), mainly due to the increased CH_4 emissions under continuous flooding.

This study revealed that 81.07% of GHG emissions came from CH_4 emissions from rice cultivation, followed by N_2O emissions from fertilizer utilization, CO_2 emissions from diesel fuel utilization, CH_4 emissions from burning rice residues, CO_2 emissions from insecticide and herbicide utilization, N_2O emissions from burning rice residues, and CO_2 emissions from gasoline fuel utilization, with sharing values of 8.57%, 3.75%, 3.72%, 1.13%, 0.93%, and 0.83%, respectively (Figure 4-4).

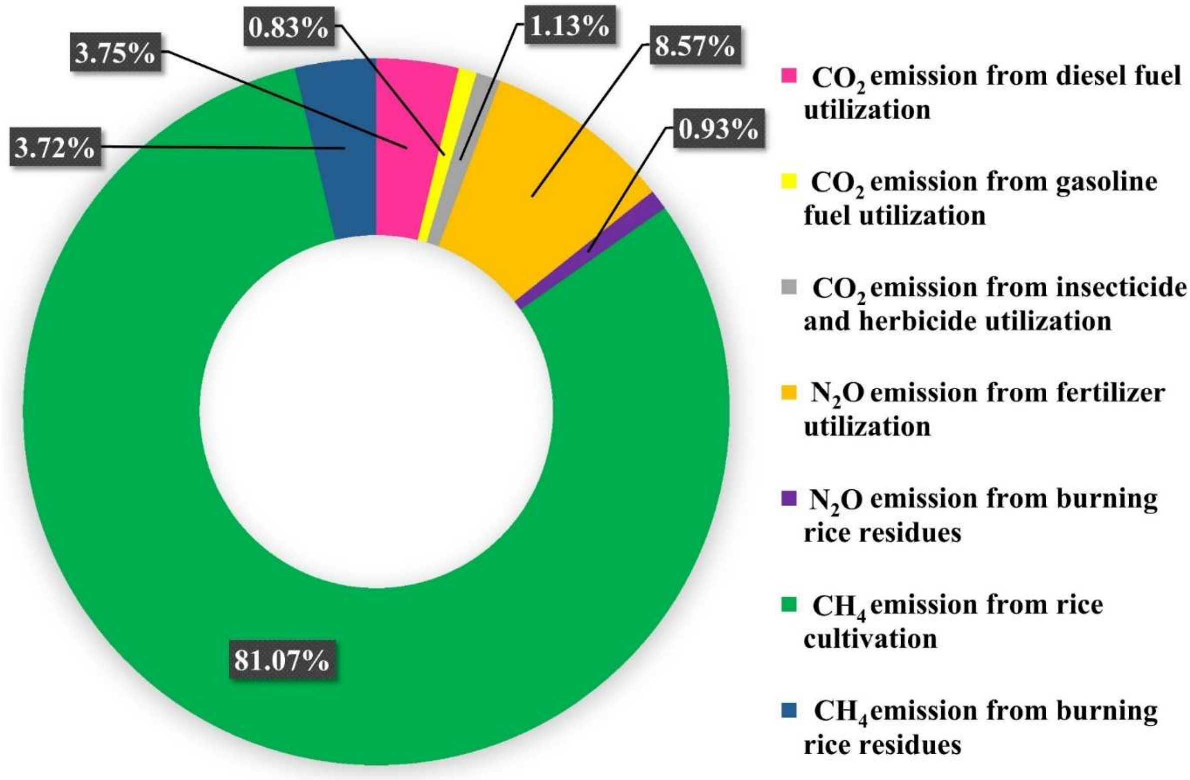


Figure 4-4 The contribution of GHG emission sources in each activity.

Table 4-4 GHG emissions within the farm gate in each activity

Site No.	**CO_2 emission** (kgCO$_2$eq ha^{-1} yr^{-1})			**N_2O emission** (kgCO$_2$eq ha^{-1} yr^{-1})		**CH_4 emission** (kgCO$_2$eq ha^{-1} yr^{-1})	
	Diesel fuel	Gasoline fuel	Insecticide and herbicide	Chemical fertilizer	Burning rice residue	Rice cultivation	Burning rice residue
I1	151	28	48	487	10	5282	43
I2	188	14	73	459	0	5418	0
I3	172	23	61	423	0	4776	0
I4	166	10	67	272	0	2404	0
I5	127	19	55	511	9	4849	37
I6	135	30	41	443	7	3616	30
I7	129	65	40	438	9	5518	38
I8	159	28	38	249	0	3805	0
I9	138	49	45	399	8	3567	31
Average	152 ± 21	30 ± 17	52 ± 13	409 ± 91	5 ± 5	4359 ± 1063	20 ± 19
R1	211	51	39	227	0	2292	0
R2	206	28	52	211	0	2153	0
R3	142	73	37	404	11	2381	45
R4	193	50	42	541	0	794	0
Average	188 ± 32	51 ± 18	43 ± 7	346 ± 157	3 ± 6	1905 ± 747	11 ± 23
p-value	0.031	0.074	0.191	0.370	0.502	0.002	0.491
Overall	163 ± 29	36 ± 20	49 ± 12	390 ± 112	4 ± 5	3604 ± 1511	17 ± 20

I = Irrigated area, R = Rain-fed area, *p*-value indicates a significant difference of value between irrigated and rain-fed areas

Table 4-5 CO_2, N_2O, and CH_4 emissions, and SOCSR, net GWP, and GHGI at all sites (Mean ± SD)

Site No.	**Total CO_2** (kgCO_2eq ha^{-1} yr^{-1})	**Total N_2O** (kgCO_2eq ha^{-1} yr^{-1})	**Total CH_4** (kgCO_2eq ha^{-1} yr^{-1})	**GWP** (kgCO_2eq ha^{-1} yr^{-1})	**SOCSR** (kg CO_2eq ha^{-1} yr^{-1})	**net GWP** (kgCO_2eq ha^{-1} yr^{-1})	**Rice yield** (kg ha^{-1} yr^{-1})	**GHGI** (kgCO_2eq kg^{-1} yield)
I1	227	497	5324	6048	938	5110	3410	1.50
I2	275	459	5418	6152	2708	3444	4600	0.75
I3	256	423	4776	5455	1581	3874	3864	1.00
I4	243	272	2404	2918	1299	1619	3684	0.44
I5	201	520	4886	5607	1367	4240	4618	0.92
I6	206	450	3647	4303	1264	3039	2430	1.25
I7	234	447	5556	6238	1068	5170	3646	1.42
I8	225	249	3805	4279	858	3421	2040	1.68
I9	232	407	3598	4237	919	3318	2954	1.12
Average	233 ± 23	414 ± 94	4379 ± 1070	5026 ± 1143	1334 ± 568	3693 ± 1091	3472 ± 882	1.12 ± 0.39
R1	301	227	2292	2821	1073	1748	3626	0.48
R2	286	211	2153	2650	974	1676	3372	0.50
R3	252	415	2426	3093	403	2690	2144	1.25
R4	285	541	794	1620	801	819	2604	0.31
Average	281 ± 21	349 ± 158	1916 ± 756	2546 ± 643	813 ± 295	1733 ± 765	2937 ± 684	0.64 ± 0.42
p-value	0.005	0.365	0.002	0.002	0.116	0.008	0.308	0.068
Overall	248 ± 31	394 ± 114	3621 ± 1519	4263 ± 1547	1173 ± 547	3090 ± 1351	3307 ± 838	0..97 ± 0.45

I = Irrigated area, R = Rain-fed area, *p*-value indicates a significant difference of value between irrigated and rain-fed areas

Table 4-6 Correlation matrix of the pertinent factors and among the GHG emissions

	Manure	N	P_2O_5	K_2O	Burning	CO_2	N_2O	CH_4	GWP	SOCSR	Net GWP	Yield	GHGI
Manure	1.00												
N	0.175	1.00											
P_2O_5	−0.335	0.447	1.00										
K_2O	0.449	0.509	0.079	1.00									
Burning	0.189	0.134	−0.224	−0.350	1.00								
CO_2	−0.216	−0.313	0.049	0.131	−0.544	1.00							
N_2O	0.216	0.925 **	0.331	0.328	0.497	−0.462	1.00						
CH_4	0.739 **	0.391	−0.088	0.436	0.322	−0.535	0.457	1.00					
GWP	0.730 **	0.452	−0.056	0.454	0.344	−0.537	0.520	0.997 **	1.00				
SOCSR	0.526	0.339	−0.126	0.787 **	−0.423	0.093	0.130	0.468	0.466	1.00			
Net GWP	0.609 *	0.372	−0.012	0.195	0.555 *	−0.640 *	0.531	0.932 **	0.936 **	0.124	1.00		
Yield	0.396	0.327	−0.14	0.832 **	−0.278	0.093	0.185	0.460	0.463	0.722 **	0.231	1.00	
GHGI	0.383	0.030	0.000	−0.323	0.656 *	−0.662 *	0.269	0.604 *	0.595*	−0.278	0.778 **	−0.400	1.00

* = Correlation is significant at 0.05 probability level ($p < 0.05$), ** = Correlation is significant at 0.01 probability level ($p < 0.01$)

4.4 Discussion

4.4.1 Rice yield and SOC under different management practices

Proper management practices can increase SOC sequestration through increasing OM inputs to the soil. Soil organic material can be mineralized towards releasing the nutrient, which subsequently can be taken up by crops to increase crop yields. Therefore, the mineralization of soil organic matter (SOM) is a vital parameter to enhance crop yields. This is consistent with our result that rice yield had a highly positive correlation with SOC (Figure 4-1) and SOCSR (Figure 4-2). Liang et al. (2012) indicated that increasing the amount of SOC could be accomplished by regular manure application with a return of more crop residues, which subsequently can lead to higher crop production. In arable land cropping systems, increasing the amount of OM in soil not only increases SOM, but also reduces net GHG emissions (Koga et al., 2006). Moreover, studies have shown that combining both organic and chemical fertilizers can be a suitable way for enriching soil (Nie et al., 2007; Hao et al., 2008). From this study, I2 and R1 reached the same rice yield and SOC, which was the highest when compared with the others (Table 4-2).

4.4.2 Effects of land management practice on CO_2, CH_4, and N_2O emissions

According to many previous studies, the estimation of GHG emissions from rice production varies, but they all agree that rice production is a significant contributor to overall emissions. As in flooded rice paddies generally, flooding rice fields block oxygen penetration into the soil, which allows bacteria capable of producing CH_4 to thrive (Wassmann et al., 2000). Rice production also generates N_2O from N-fertilizer application (Yang and Wang, 2007). Meanwhile, the main sources of CO_2 emissions are either cropping operations, such as tillage, sowing, harvesting, or transport, including stationary operations, such as pumping water, spraying, and grain drying. The burning of rice residue is another emissions source yielding

CO_2, CH_4, and N_2O (Duan et al., 2004). This study revealed that the land management practice of highly burned rice residues generated high CH_4, and N_2O emissions as was seen at site R3 (Table 4-4). In addition, more fuel consumption in rain-fed areas than in irrigated areas was found, owing to the energy needed for pumping water into rain-fed rice fields and farm operations, such as herbicide application, because the dry land would face weeds more than flooded land would. Consequently, these management practices can also produce higher amounts of CO_2eq than others can (Snyder et al., 2009).

CH_4 is produced from the decomposition of OM in anaerobic conditions by methanogens. SOM is the most common limiting factor for methanogenesis in rice fields (Wang et al., 2000). OM arises from the four main sources of animal manure, green manure, crop residues (straw, stubble, roots), and by-products of rice production (root exudates, sloughed-off root cells, and root turnover). Neue et al. (1996) reported that the rice straw application of 5 Mg ha^{-1} yr^{-1} increased CH_4 emissions ten-fold compared to the use of only urea fertilizer. To reduce the CH_4 emissions associated with water management in rice fields in which alternating wetting and drying could reduce more CH_4 emissions than continuously flooded fields (Adhya et al., 200). These results were in complete agreement with our findings that the land management practices for site I7 (Table 4-5) caused the highest CH_4 emissions due to the higher manure application and amount of burned rice residues than at other sites. Additionally, irrigated areas had higher CH_4 emissions than rain-fed areas did, owing to the longer period of flooding in rice fields, which was similar to previous investigations by Bhattacharyya et al. (2012) and Shen et al. (2014). This result was obtained from sites I1 to I9, with an average value of 4379 kg CO_2eq ha^{-1} yr^{-1} for irrigated areas, and sites R1 to R4, with the average value of 1916 kg CO_2eq ha^{-1} yr^{-1} for rain-fed areas. However, the addition of organic material such as rice residues and manure application lead to increasing CH_4 emission due to anaerobic decomposition (Chidthaisong and Watanabe, 1997), but it can greatly offset the mitigation benefits of soil carbon sequestration (Lu et al., 2014). This can obviously be found at site I2 where applied manure and no burning rice residues, with the high SOCSR (2, 708 kg CO_2eq ha^{-1} yr^{-1}) and low GHGI (0.75 kgCO_2eq kg^{-1} yield) (Table 4-5). Based on our study, we, therefore, support the addition of manure application and returning rice residues to the soil because these practices not only gain more C storage in the soil than is release to the atmosphere but also can enhance soil fertility through the mineralization of SOM, which in turn will increase crop productivity.

Fertilizer application is important from a climate change perspective due to energy intensive production, and the positive relationship with N_2O emissions from soils (Zou et al., 2008; Liu et al., 2012). This was consistent with our result of the land management practices at site I5 (Table 4-5), which generated the highest N_2O due to the high chemical fertilizer application and amount of burned rice residues that was practiced.

4.4.3 Effects of land management practice on net GWP and GHGI

The net GWP has been illuminated to understand agriculture's impact on radiative forcing (Linquist et al., 2012). Therefore, net GWP and GHGI need to be considered when evaluating a management strategy for mitigating GHG emissions. Our study found that more burning rice residues greatly contributed to high net GWP and GHGI. Our results were consistent with Zhang et al. (2014), whose study showed that a chemical fertilizer application rate of 210 kg N ha^{-1} yr^{-1} was the most suitable for balancing GHG emissions and rice yield in Chongming Island, Eastern China. In this study, the average GHGI was 0.97 kg CO_2eq kg^{-1} yield. In Jiangsu province, China, the GHGI varied from 0.41–0.74 kg CO_2eq kg^{-1} yield under annual rice-wheat rotations with integrated soil-crop system management (Ma et al., 2013). Qin et al. (2010) studied midseason drainage and organic manure incorporation in Southeast China and found that the GHGI varied from 0.24–0.74 kg CO_2eq kg^{-1} yield, which was lower than in this study. In Thailand, the study of Yodkhum and Sampattagul (2014) who applied a life cycle assessment concept and carbon footprint of product to determine GHG emissions of rice production in Thailand, reported that in northeast Thailand, GHG emissions of KDML 105 of NongKhai was 2.39 kg CO_2eq kg^{-1} yield, which was higher than in this study. Arunrat et al. (2016) estimated GHG emissions based on the concept of the life cycle assessment of the greenhouse gas emissions (LCA-GHG) of products in Phichit province of Thailand. Their results revealed that GHG emissions from rice production varied from 1.81-2.87 kg CO_2eq kg^{-1} yield, and 1.72-2.70 kg CO_2eq kg^{-1} yield for irrigated and rain-fed areas, respectively, which was higher than in this study. However, the report of the Office of Agricultural Economics about the GHG emissions estimation and database developments in Thailand in 2012 using the methodology of life cycle assessment of greenhouse gas emissions of products and IPCC guideline. The GHGIs ranged from 0.67 to 3.96 kg CO_2eq kg^{-1} yield and averaged 2.32 kg CO_2eq kg^{-1} yield (OAE, 2012). Taking the country's value as the baseline, the GHGI in this study was lower than the country's average. This is because the GHG emissions that occur outside the farm gate were not included in this study such as raw materials production, the transportation of agricultural inputs from manufacturing to the farm, and the transportation of rice production from the farm to the mill and storehouse. This study emphasized the balance between GHG emissions and SOC sequestration on the effect of land management practices because the SOC content at local-scale data in the estimation of GHGI which is usually limited data available due to high uncertainties in the large-scale data (Wang et al., 2015). Reasonable land management practices are the main components for mitigating GHG emissions because CO_2, CH_4, and N_2O emissions would be negated by the benefits of SOC sequestration. It is possible that the goal of reducing the net GWP and GHGI in Thailand should focus on increasing the SOC and simultaneously decreasing the burning rice residues.

4.5 Conclusions

This study showed that the amount of K_2O fertilizer applied is the most significant factor explaining rice yield and SOCSR in this area. The contributions of CO_2, CH_4, and N_2O to net GWP decreased in the order from $CH_4 > N_2O > CO_2$ at all sites. GHGI had a positive correlation with the amount of burned rice residues, CH_4 emission, GWP, and net GWP. The land management practices that led to low GHGIs were those that returned residues to the field after harvesting and incorporated manure and chemical fertilizers. These practices are an effective way to reduce GHG emissions and contribute to sustainable rice production for food security with low GHGI and high productivity.

Chapter 5

Using the EPIC model to predict local-scale impact of climate change on rice yield and soil organic carbon sequestration in a tropical monsoon area

5.1 Introduction

Climate change and rising atmospheric CO_2 may influence rice yields (Rosenzweig et al., 2001; Parry et al., 2004; Adejuwon, 2005; Wassmann and Dobermann, 2007) and thus threaten food security (Nguyen, 2006). Although soils have the potential to mitigate increasing CO_2 concentrations through carbon (C) sequestration, land misuse and soil mismanagement have caused depletion of soil organic carbon (SOC) (Lal, 2004a; Li and Zhang, 2007; Li et al., 2010). Therefore, computer simulation models of soil, crop yields, and atmospheric systems can make valuable contributions to determine crop responses, predict crop performances, and evaluate the environmental impacts of different management practices.

The Environmental Policy Integrated Climate (EPIC) model, a notable integrated model of management of the soil–water–atmosphere system, was developed and has been successfully used to simulate the effects of this system on crop production and soil dynamics (Williams et al., 1984; Williams et al., 1989; Sharpley and Williams, 1990). Williams et al. (2006) noted that the EPIC model can also be used to simulate nitrogen (N) and C cycling, surface runoff and leaching of N and phosphorous (P), alternative cropping systems, management practices, crop growth and yields of about 100 different crop plant species, climate change, and the effects of atmospheric CO_2. According to Zhao et al. (2013), the EPIC model is the most suitable model for SOC simulation for different irrigation, fertilization, and tillage treatments. With increasing concern about climate change and associated issues, the

EPIC model has increasingly been used to simulate the impacts of climate change on crop yields (Lee et al., 1996; Phillips et al., 1997; Brown, Rosenberg, 1997; Brown et al., 2000; Izaurralde et al., 2003; Wang and Li, 2010), SOC (Causarano et al., 2007; 2008; Gaiser et al., 2008; Zhang et al., 2010; Balkovič et al., 2011), and nitrate leaching (Chung et al., 2001). However, these studies have been conducted at large scales (basin, country or regional), at which local heterogeneity in factors such as local climate, soil properties, and farmer management practices could not be incorporated. The impacts of climate change at different scales may differ in severity. Indeed, local-scale simulation is often challenging because precise data are rarely available and accessible. For instance, Xiong et al. (2008) examined the performance of CERES-Rice at a regional scale across China using a cross-calibration process based on limited experimental data, agroecological zones, and a geographical database with a 50 km × 50 km grid scale; reducing the error between the simulated and actual yields using specific areas and other yield loss factors was suggested. Niu et al. (2009) reported that the use of field measurement data or location-specific data instead of data from widely available sources decreased the simulation bias in a study in which the EPIC model was used to simulate grain sorghum yields in the US Great Plains under different climate scenarios. Xiong et al. (2014) suggested that more precise data at the local or regional scale could improve the reliability and accuracy of model calibration even for global simulation of rice yields with the EPIC model. Moreover, evaluation of climate change impacts on rice yield (Pumijumnong and Arunrat, 2013; Arunrat and Pumijumnong, 2015), N loss (Arunrat and Pumijumnong, 2014) and SOC sequestration (Arunrat et al., 2014) in rice field were performed in Thailand (country-scale) using EPIC model version0509. These studies reported that the EPIC model has never been used in Thailand before. Therefore, it needs to be more specific in order to improve the accuracy of the models, particularly location-specific data.

To fill a remaining gap in this research, there is a pressing need to improve the accuracy of EPIC model simulations through the use of location-specific data for model calibration and validation. The objectives of this study are: 1) to evaluate the reliability of EPIC model calibration and validation processes based on local-scale data, and 2) to evaluate the possible impacts of climate change on rice yield and SOC sequestration. Our findings contribute to understanding the consequences of long-term climate change, which is essential for agricultural policy-making and the selection of mitigation strategies.

5.2 Materials and methods

5.2.1 Site description

The study area is in the Thung Kula Sub-district, Suwannaphum District, Roi Et Province, Thailand, located at 15°28′N, 103°48′E, and covers 59.45 ha, 22.29 ha of which is irrigated and 37.16 ha rain-fed. Roi Et soils are derived from washed deposits of sandstone and occur on the lower parts of peneplains. The elevation ranges from 100 to 200 m above sea level. This area has a tropical monsoon climate (Köppen 'Aw'). The average annual precipitation in 2014 ranged from 800 to 2,900 mm, and the mean annual air temperature ranged from 26 to 28°C. The major soil type in Roi Et Province is Ultisol with > 60% sand content; low SOC, ranging from 0.40%–1.29%; and moderately acidic surface soil with a pH range of 5.0–6.0 (LDD, 1991). In the study area, there are six soil series: a) *Ki* (Kula Ronghai series): fine-loamy, mixed, active, isohyperthermic Typic Natraqualfs; b) *Nn* (Nakhon Phanom series): fine, kaolinitic, isohyperthermic Aeric Plinthic Paleaquults; c) *Ph* (Phan series): fine, kaolinitic, isohyperthermic Typic (Plinthic) Endoaqualfs; d) *Pm* (Phimai series): very fine, smectitic, isohyperthermic Ustic Endoaquerts; e) *Sp* (San Pa Tong series): coarse-loamy, siliceous, semiactive, isohyperthermic Typic (Kandic) Paleustults; and f) *Tt* (Tha Tum): fine, mixed, semiactive, isohyperthermic Aeric (Plinthic) Endoaqualfs (LDD, 2003) (Figure 5-1). In general, these soils are deep, and characterized by a number of different colors, although the dominant color characteristics are a grayish-brown or light brown sandy loam A horizon overlying a light brown grading to pinkish-gray sandy clay loam or loam kandic B horizon, which, in turn, overlies a light gray or whitish clay loam or clay C horizon. The soils are mottled throughout the profile, with strong brown, yellowish brown or dark brown and some yellowish red or red mottles common in the subsoil. The soil reaction is moderately acidic over strongly to very strongly acidic (LDD, 2003).

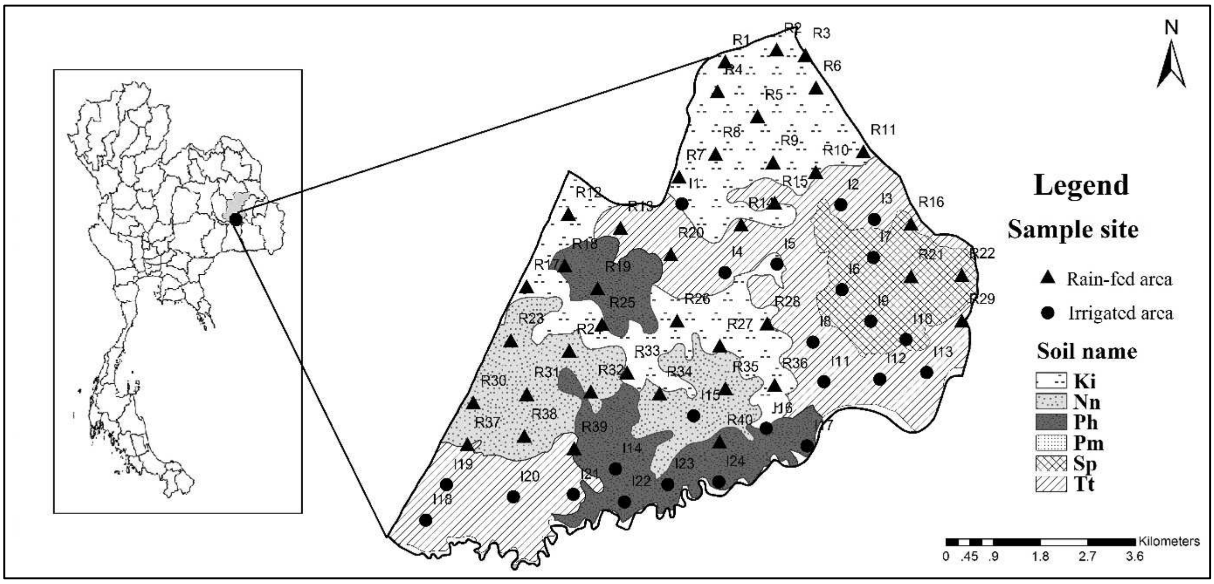


Figure 5-1. Study area and soil series (LDD, 2003)

5.2.2 EPIC model description

5.2.2.1 Crop growth model

The EPIC model is able to simulate the growth of both annual and perennial crops based on a single crop growth model. This model uses radiation-use efficiency to calculate the photosynthetic production of biomass. Interception of solar radiation is estimated as a function of leaf area index (LAI). LAI is simulated with equations determined based on heat units, the maximum LAI for the crop, genetic coefficients, and five environmental stresses (water, temperature, nutrients (N and P) and aeration) (Easterling et al., 1998; Liu et al., 2014). The stress factor values range from 0 to 1, and the phonological development of the crop is based on daily heat unit accumulation and a heat unit index value (HUI) computed from 0 at planting to 1 at maturity. The potential biomass is adjusted daily through multiplying by the lowest value of the five environmental stress indices. The water stress index is the ratio of soil available water to the potential water demand of a crop. The temperature stress index is computed using a function dependent upon the daily average temperature, the optimal temperature, and the base temperature for crop growth. The N and P stress indices are based on the ratios of accumulated plant N and P to the optimal values of N and P. The aeration stress index is estimated as a function of soil water relative to porosity in the root zone (Tan and Shibasaki, 2003). Atmospheric CO_2 concentration also influences photosynthesis by increasing radiation-use efficiency. Therefore, crop yields are estimated by multiplying the above-ground biomass at maturity (determined based on the accumulation of heat units or a specified harvest date) by a harvest index (economic yield divided by aboveground biomass) specified for the particular crop (Easterling et al., 1998; Liu et al., 2014).

5.2.2.2 Carbon flows in the EPIC model

The EPIC model simulates dynamic C processes using C routines conceptually similar to those used in the Century model (Izaurralde et al., 2001; 2006). The Century model (Parton et al., 1987; 1994) was successfully used to simulate soil organic matter (SOM) across a variety of land use types and climates and is among the models that consistently produce low errors and show low overall bias (Kelly et al., 1997; Smith et al., 1997). The total C pool for soil C estimations consists of five compartments: structural litter, metabolic litter, microbial biomass, slow humus, and passive humus. Parton et al. (1987; 1993; 1994) and Izaurralde et al. (2006) described the original dynamic C processes in the Century model and the new C and N modules developed for the EPIC model. These new modules were built to connect simulation of soil C and N dynamics with crop management, tillage methods, and erosion processes. The surface microbial pool turnover rate is independent of soil texture, whereas soil texture influences the turnover of active SOM (higher rates for sandy soils). The model assumes a 60% loss of carbon due to microbial respiration for surface microbes and 55% for all other layers. Allocation of carbon from lignin in structural litter to CO_2 is set at 0.3, and the rest is partitioned into slow humus (Izaurralde et al., 2006). In each process, there are moisture and temperature controls on soil biological processes (Figure 5-2).

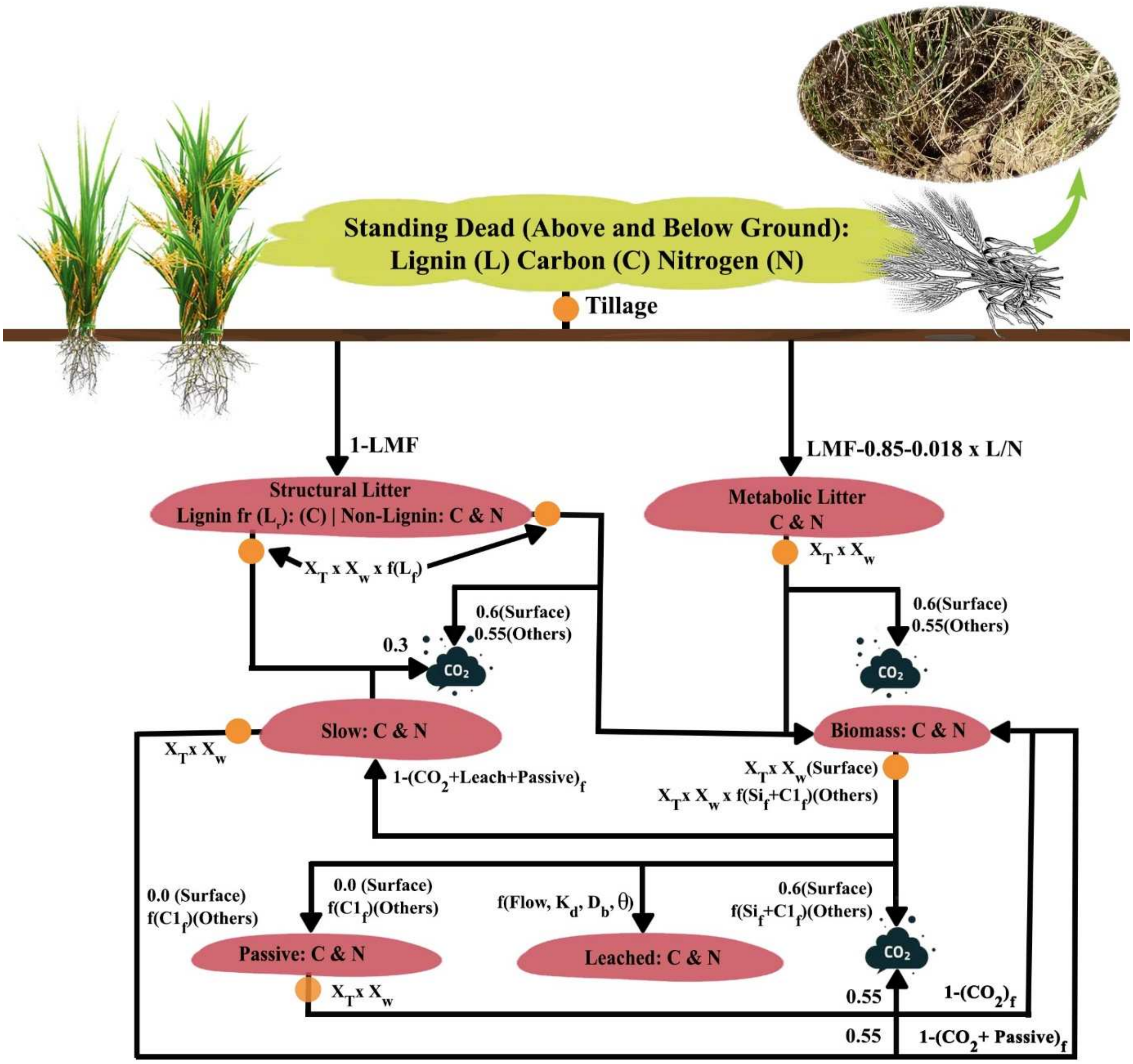


Figure 5-2 Carbon flows in the EPIC model. X_W and X_T refer to moisture and temperature controls on soil biological processes; *LMF* = fraction of the litter that is metabolic (kg kg^{-1});

Lf = fraction of structural litter that is lignin (kg kg^{-1}); lowercase f = "function of"; subscript f = "fraction"; Sif = fraction of soil mineral component that is silt; Clf = fraction of soil mineral component that is clay; K_d = distribution coefficient of organic compounds between the soil solid and liquid phases; DB = soil bulk density; θ = soil volumetric water content (after Izaurralde et al., 2006)

5.2.3 Data collection and model input data

5.2.3.1 Simulation unit

The study area was divided into small sub-areas to collect soil samples, prepare climate data, and determine land management characteristics using a polygonal grid measuring 0.01 × 0.01 degrees in size, and covering ~1 × 1 km. The total area was 59.45 ha and covered a total of 64 grid cells, with 22.29 ha and 24 cells in irrigated areas, and 37.16 ha and 40 cells in rain-fed areas (Figure 5-3).

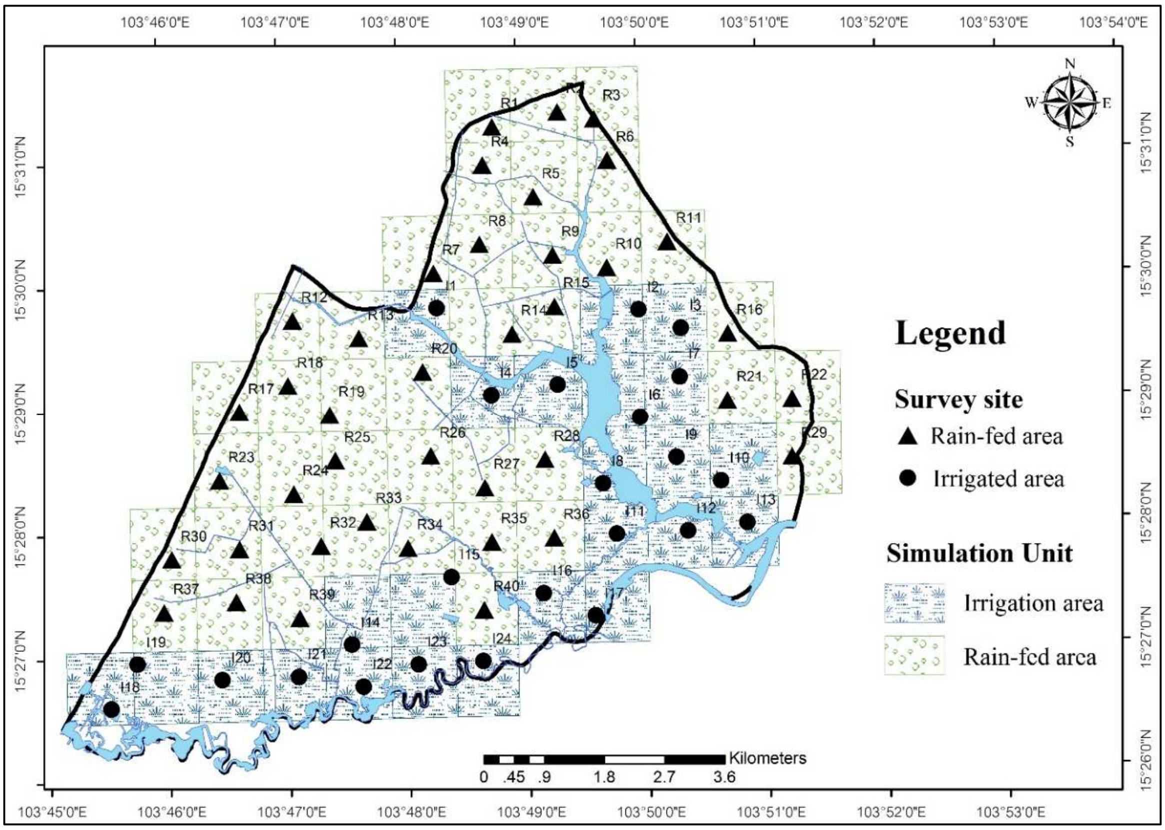


Figure 5-3 The location of data collection and simulation unit

5.2.3.2 Soil sampling and analysis

In a survey of soil nutrient status in Thailand from 2004 to 2008, 13 sites in the study area were sampled by the laboratory of the Office of Science for Land Development, Land Development Department, Ministry of Agriculture and Cooperatives, Thailand. From the 13 sites in the study area in Thung Kula Sub-district, nine of which were in irrigated areas and four in rain-fed areas, data were collected and the SOC estimated in 2004. In 2014, soil samples were collected again from the same 13 study sites to investigate changes in soil properties and model calibration, and 51 new sites were also investigated for model validation. Soil samples were collected during the dry season after the rice harvest (November, 2014). At each site, the soil horizons from 0 to 40 cm in depth were identified based on specific physical features, i.e., color and texture. Three samples (replications) of each soil horizon were then collected. A total of 621 soil samples from 64 sites were collected. The soil parameters required for the model and their values are listed in Table 5-1.

Soil texture (%; sand, silt, and clay), bulk density, pH, SOC, electrical conductivity (EC), cation exchange capacity (CEC), and total nitrogen (TN) were analyzed in the laboratory. The physical and chemical properties of whole soils were determined using the procedures described by the National Soil Survey Center (1996). After each sample was left for a 24-hr drying period in an oven at 105°C, soil bulk density was determined as the dry weight per unit volume of the soil core. Soil texture was determined using a hydrometer, and soil pH was determined in a 1:2.5 soil to water mixture using a pH meter. The EC of saturated paste extracts was measured following the method described by the United States Department of Agriculture (USDA, 1954). CEC was determined with the pH 7.0 1 M ammonium acetate (NH_4OAc) method. Total N was measured using the Kjeldahl method. Available phosphorus content was determined using the Bray II method, and phosphorus concentration was measured using the molybdate blue method (Bray and Kurtz, 1945). Extractable potassium (K) was extracted from the soil samples with pH 7.0 NH_4OAc, and element concentrations were measured with a flame photometer. Organic C content was determined using the method of Walkley and Black (1934). SOC stock was calculated as:

$$SOC = (BD \times OC \times D) \times 10 \qquad (1)$$

where *SOC* is the soil organic carbon stock (Mg C ha^{-1}), *BD* is the soil bulk density (Mg m^{-3}), *OC* is the organic carbon content (g kg^{-1}), and *D* is the soil sampling depth (m). In this study, the soil depth was not fixed, but depended on the soil sampling depth of each horizon.

Table 5-1 Characteristics of main soil properties (0–40 cm) required for the model at the 64 sites

Soil variables	Ranges	Source
Bulk density (Mg m^{-3})	0.71-1.78	This study
Wilting point at 1500 kPa (m^3 m^{-3})	0.02-0.08	LDD (2003)
Field capacity at 33 kPa (m^3 m^{-3})	0.110-0.187	LDD (2003)
Sand (Ø 0.05–2 mm) (%)	47.0-86.0	This study
Silt (Ø 0.002–0.05 mm) (%)	0.10-23.9	This study
Total nitrogen (g kg^{-1})	0.045-0.94	This study
Available phosphorus (mg kg^{-1})	25.3-102	This study
pH	3.86-6.66	This study
Organic carbon (g kg^{-1})	0.34-3.22	This study
Cation exchange capacity (cmol ckg^{-1})	2.31-7.52	This study
Exchangeable K concentration (mg kg^{-1})	4.97-132	This study
Electrical conductivity (mmho cm^{-1})	0.01-0.17	This study

5.2.3.3 Climatic data

The EPIC model requires the following monthly climate variables: maximum and minimum air temperature, precipitation, rain days, solar radiation, and relative humidity. In this study, average values of the climatic data were calculated for two separate periods. First, data for the baseline period (1986–2014) was retrieved from the Thai Meteorological Department for calibration and validation of the model. Secondly, future climate changes under the A2 and B2 scenarios were modeled to assess the impact of climate change on rice yields and changes in SOC. The A2 scenario assumes a world emphasizing self-reliance, the preservation of local identities and economic growth, with a slowly, continuously increasing global population, and technological change more fragmented and slower than in other storylines. In contrast, the B2 scenario assumes local solutions to economic, social, and environmental sustainability, intermediate levels of economic development, less rapid and more diverse technological change than in the B1 and A1 storylines, and continuously increasing global population, at a rate lower than in A2 (IPCC, 2001; 2007). In this study, two long-term periods (2015–2045 and 2045–2075) under the A2 and B2 climate change scenarios were modeled, as proposed by the Southeast Asia START (System for Analysis, Research and Training) Regional Centre (SEA START RC), at high resolution with a grid size 20 × 20 km (0.22°). Data were simulated using the PRECIS (Providing REgional Climates for Impacts Studies) regional climate model, and the Global Circulation Model (GCM) ECHAM4 dataset was used as the initial data for calculations (SEA START RC, 2010). As described by Arnell et al. (2004), the CO_2 concentration for baseline period was kept constant at 360 ppm, and the CO_2 concentrations used for 2015–2045 and 2045–2075 were 490 and 629 ppm, respectively, in the A2 scenario, and 455 and 525 ppm, respectively, in the B2 scenario.

5.2.3.4 Management practice

Management practice data was considered for the two periods. First, the data collected in 2004 was used for model calibration. However, fertilizer application rate data were not available for 2004. Therefore, the trend of fertilizer application rates from 2010 to 2014 was employed using simple linear regression analysis and fitting a linear equation. We found that the average rate of increase was of 1.52 kg ha^{-1} yr^{-1} (1.77% yr^{-1}), which is consistent with Bangkok bank (2003) estimate of the Thailand agricultural sector's chemical fertilizer usage from 1995 to 2003. For this 8-year period, the average rate of increase was 1.3% yr^{-1}. Secondly, management data were obtained through field surveys over a 5-year period (2010–2014); these data were used for model validation and fixed for each site for model simulation under the A2 and B2 climate change scenarios.

Questionnaires were administered at each sampling site to record the crop and management practices of farm owners. At farmers at each of the 64 sites recorded crop and land management data. Rice yields and management practice data (i.e., dates of planting and harvesting; rates of application of fertilizers, manure, pesticides, and irrigation; and field operations performed) were obtained from the questionnaire surveys in 2014 and from the record books for the standards for good agricultural practices (GAP) of farm owners over the 5-year study period (2010–2014), including both rainy and dry seasons. These record books were disseminated to the farmers by the Department of Agricultural Extension, Ministry of Agriculture and Cooperatives, Thailand to record agricultural activities, which helped with the collection of precise operational practice data for this study.

Rice in the study area refers to the major rice crop, which is grown during the rainy season between July and December, and the second rice crop, which is grown during the dry season between January and April of the following year (OAE, 2014). Most rice fields in the study area use rain-fed cultivation, in which rice is grown only once a year because precipitation is a major limiting factor. Farmers in some irrigated areas are able to grow rice twice a year, for both major and second rice crops. Jasmine rice (*Oryza sativa*) is mostly commonly grown in this area. The dominant rice varieties recorded in this study were Khao Dawk Mali 105 (KDML 105), RD 6, and Suphanburi 60. KDML105 and RD 6 are strongly photoperiod sensitive and flower in late October, regardless of sowing time, whereas Suphanburi 60 is a non-photosensitive rice variety. Based on the field survey data, each site was input into the EPIC operation schedule file with the respective farmers' actual management practices specified. Five main types of management operations that were incorporated in the EPIC model: seeding/planting, tillage, irrigation, fertilizing, and harvesting. For each type of management operation, the exact date and month, amount and type of fertilizers, crop type, and irrigation conditions were also specified. The main conventional management techniques used in the study area are the following.

First, during the growing period, both major and second rice crops were cultivated using the broadcast method and harvested by machine.

Second, for tillage management, conventional tillage to a depth of 20 to 30 cm was performed by machine, with two different situations distinguished between wet and dry soil surface conditions.

Third, after harvesting, farmers applied one of two forms of rice straw and stubble management: incorporation into the soil or burning in the field. The farmers usually burn rice residue after major rice harvesting (dry season) because of the ease and convenience of tillage to prepare for the next crop. Irrigated areas had lower amount of burned rice residue than rain-fed areas, with averages of 0.071 and 0.141 Mg ha^{-1}, respectively.

Fourth, for water management, continuous flooding and shallow flooding were used for the irrigated and rain-fed areas, respectively. In irrigated areas, the fields were inundated with 10 to 15 cm of standing water throughout the growing period and drained or naturally dried 7 to 10 days before harvesting. In rain-fed areas, the soil was flooded temporarily, depending on rainfall, or water pumping when rain water was unavailable. Therefore, if the field was not in an irrigated area, the irrigation code was set as dryland conditions.

Fifth, for manure and chemical fertilizer application, cattle manure was often added to the soil as basal fertilizer once a year, usually after the previous crop was harvested or at the beginning of planting the next crop. The average manure application rate was 2.23 and 1.15 Mg ha^{-1} for sites in irrigated and rain-fed areas, respectively, and was higher in the irrigated areas compared to the rain-fed areas. The following chemical fertilizer types were found in the study area: 46-0-0, 16-16-8, 16-20-0, 0-0-60, 15-15-15, and 16-8-8. A higher fertilizer application rate was indicated for irrigated areas than for rain-fed areas, with average rates of 320 and 260 kg ha^{-1}, respectively.

5.2.4 Sensitivity analysis

Variation of model output can be arisen from two ways: user adjustable parameters and the model handles some parameters based on input variables (Owen et al. 2015). In this study, sensitivity analysis of adjustable parameters was performed to assess the relative importance of crop growth and carbon cycle parameters to model output, as presented in Table 5-2. Moreover, weather data (i.e. maximum temperature, minimum temperature, solar radiation, precipitation, and relative humidity) and management data (i.e. amount of N, P_2O_5, and K_2O fertilizers, manure and rice residues applications) were considered to test the sensitivity of model outputs to varying of input variables, as presented in Tables 5-3 and 5-4. Both adjustable parameters and input variables are important for rice yield and SOC because there are many functions that differ in their relative importance for yield and SOC predictions. Especially, it is valuable to understand which variables are the most important for simulation accuracy. Users can pay attention which variables need accurate values for improving input data sets.

The main purpose of sensitivity analysis is to determine the magnitude of changes in the model's response associated with changes in the value of a specified parameter. In this study, The one-factor-at-a-time (OAT) method was used to calculate relative sensitivity indices for rice yields and SOC. A total of five parameters for crop growth, ten parameters for the C cycle, five variables for weather data, and five variables for management data were varied by ± 10% of the default model values to assess sensitivity using the equation derived from Liu (2009) below,

$$S = \frac{\Delta Y}{\Delta X} \frac{X}{Y}, \tag{2}$$

where *S* is the sensitivity index of the effect of parameter X_i on *Y*, *Y* is the model output (i.e. rice yield and SOC in this study), ΔX is a small change in *X*, and ΔY is the change in *Y* in response to the change in *X*.

Based on equation (2), the sensitivity indices for rice yield and SOC are determined as follows:

$$\bar{S}_{yieldi} == \frac{\left|Yield_{1.1X_i} - Yield_{X_i}\right| + \left|Yield_{0.9X_i} - Yield_{X_i}\right|}{0.2Yield_{X_i}}, \tag{3}$$

$$\bar{S}_{SOCi} == \frac{\left|SOC_{1.1X_i} - SOC_{X_i}\right| + \left|SOC_{0.9X_i} - SOC_{X_i}\right|}{0.2SOC_{X_i}}, \tag{4}$$

where $\bar{S}_{yieldi}$ and $\bar{S}_{SOCi}$ are the sensitivity indices of parameter *Xi* for rice yield and SOC, respectively; $Yield_{X_i}$ and SOC_{X_i} are the rice yield and SOC, respectively, simulated by setting all parameters to default values; $Yield_{1.1X_i}$ and $SOC_{1.1X_i}$ are the rice yield and SOC, respectively, simulated by setting all parameters to default values except *Xi*, which is set to 110% of its default value; and $Yield_{0.9X_i}$ and $SOC_{0.9X_i}$ are the rice yield and SOC, respectively, simulated by setting all parameters to default values except Xi, which is set to 90% of its default value. The parameters with the highest $\bar{S}_{yieldi}$ and $\bar{S}_{SOCi}$ values are defined as the most sensitive parameters for rice yield and SOC, respectively. The range of sensitivity indices is between 0 (non-sensitive) to 1 (very strongly sensitive); higher values indicate higher sensitivity.

Table 5-2 Crop- and carbon cycle-related default values, suggested range, and calibrated values in the EPIC model

No	Parameter	Symbol	Default value	Suggested range*	Calibrated value
Crop parameters					
1.	Biomass-energy ratio (kg ha^{-1} MJ^{-1} m^{2})	WA	25	20-30	25
2.	Harvest index	HI	0.5	0.4-0.5	0.45
3.	Potential heat units (°C)	PHU	1580	1200-2400	1630
4.	Water stress–harvest index	PARM(3)	0.5	0.3-0.7	0.5
5.	SCS curve number index	PARM(42)	1.5	0.5-2.0	1.0
Carbon cycle parameters					
1.	Fraction of humus in the passive pool	FHP	0.0	0.3-0.7	0.6
2.	Fraction of slow C allocated to passive pool	PARM(45)	0.05	0.001-0.05	0.05
3.	Slow humus transformation rate, d^{-1}	PARM(47)	0.000548	0.00041-0.00068	0.000562
4.	Passive humus transformation rate, d^{-1}	PARM(48)	0.000012	0.0000082-0.000015	0.000013
5.	Microbial activity at top soil layer	PARM(51)	1.0	0.1-1.0	1.0

6.	Residue decay tillage coefficient	PARM(52)	20.0	5.0-15.0	14.5
7.	Microbial activity at depth	PARM(53)	0.9	0.8-0.95	0.89
8.	Root growth water use coefficient	PARM(54)	5.0	2.5-7.5	5.7
9.	Root growth water use/depth ratio	PARM(55)	0.5	0.0-1.0	0.8
10.	Root growth depth coefficient	PARM(56)	10.0	5.0-10.0	10.0

* EPIC suggested range

Table 5-3 Monthly weather data for testing the sensitivity of model outputs to varying of input variables.

		Maximum Temperature (°C)	Minimum Temperature (°C)	Solar radiation (MJ m^{-2})	Precipitation (mm)	Relative humidity (fraction)
January	Range	24.3-26.6	16.5-16.8	15.4-16.1	4.32-19.83	0.67-0.73
	Mean±SD	25.7±1.2	16.6±0.2	15.7±0.3	13.2±7.47	0.70±0.02
February	Range	26.3-31.0	18.8-20.1	17.5-18.5	25.4-47.3	0.65-0.76
	Mean±SD	29.3±2.6	19.6±0.6	18.0±0.4	37.8±12.9	0.69±0.03
March	Range	28.4-35.8	21.0-24.6	20.9-21.5	54.8-115.0	0.64-0.72
	Mean±SD	33.3±4.2	23.3±2.0	21.2±0.3	77.4±32.6	0.69±0.02
April	Range	30.2-36.8	23.3-26.8	22.1-22.9	87.56-169.4	0.68-0.76
	Mean±SD	34.6±3.8	25.5±1.9	22.6±0.3	92.4±30.5	0.71±0.03
May	Range	29.7-32.5	23.8-27.8	20.7-22.0	150.5-436.7	0.73-0.81
	Mean±SD	34.1±3.9	26.1±2.1	21.5±0.6	263.4±140.6	0.76±0.02
June	Range	29.7-36.9	24.8-26.3	16.3-16.5	320.7-450.6	0.75-0.83
	Mean±SD	31.3±1.4	26.1±2.1	16.4±0.1	393.5±70.2	0.79±0.03
July	Range	29.1-30.9	24.3-25.8	14.1-15.3	480.8-645.3	0.78-0.85
	Mean±SD	30.2±1.0	25.5±0.8	14.7±0.5	572.7±97.8	0.82±0.02
August	Range	28.6-30.5	23.9-25.4	14.2-15.7	340.5-570.2	0.82-0.85
	Mean±SD	29.7±1.0	24.6±0.7	15.0±0.6	434.1±112.9	0.84±0.01
September	Range	28.7-31.9	23.8-24.7	18.2-19.6	224.5-404.7	0.77-0.87
	Mean±SD	30.7±1.7	24.1±0.5	18.9±0.8	306.4±76.3	0.82±0.03
October	Range	28.5-31.9	22.4-23.4	18.9-19.3	65.3-172.7	0.73-0.83
	Mean±SD	30.7±1.7	22.9±0.5	19.1±0.2	116.2±49.5	0.78±0.03
November	Range	27.0-29.2	19.6-20.6	16.3-16.6	3.2-40.1	0.71-0.77

	Mean±SD	28.2±1.1	20.1±0.5	16.4±0.2	18.9±17.4	0.74±0.02
December	Range	24.5-27.1	16.8-18.2	14.9-15.2	4.5-28.3	0.67-0.75
	Mean±SD	26.0±1.4	17.4±0.7	15.0±0.1	13.3±8.6	0.71±0.02

Table 5-4 Management data for testing the sensitivity of model outputs to varying of input variables.

Management data	**Range**	**Mean±SD**
N fertilizer (kg ha^{-1})	26.08-113.06	81.19±15.98
P_2O_5 fertilizer (kg ha^{-1})	0.0-49.04	26.49±11.06
K_2O fertilizer (kg ha^{-1})	0.0-71.04	13.43±12.33
Manure (kg ha^{-1})	0.0-4.85	1.53±1.52
Rice residues (kg ha^{-1})	0.0-3.22	3.29±2.55

5.2.5 Model calibration and validation

Five parameters for crop growth and ten parameters for the C cycle were selected to calibrate in the EPIC model, as suggested by Wang et al. (2005) and Causarano et al. (2007); these parameters are listed in Table 5-2. The calibration procedure for the crop growth and SOC modules applied data from the 13 study sites sampled in 2004. Rice yields were measured values collected from the Agricultural Statistics of Thailand report for 2004, which was generated by the Office of Agricultural Economics (OAE), Ministry of Agriculture and Cooperatives (MOAC), Thailand. The SOC measurements were collected by the Land Development Department of Thailand in 2004. The model validation procedure focused on the measured values at all sites (64 sites), which were collected over 5 years (2010–2014) for rice yield, and in 2014 for SOC.

5.2.6 Model performance evaluation

Model calibration and validation were evaluated using two criteria: the coefficient of determination (R^2), and the Nash–Sutcliffe model efficiency coefficient (*Ens*) (Nash and

Sutcliffe, 1970). In this study, the model performance was considered satisfactory if $R^2 > 0.5$ (Santhi et al., 2001) and $Ens \geq 0.60$ (Wang et al., 2012).

R^2 is defined as:

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(M_i - \bar{M}_i)(S_i - \bar{S}_i)}{[\sum_{i=1}^{n}(M_i - \bar{M}_i)^2]^{0.5}[\sum_{i=1}^{n}(S_i - \bar{S}_i)^2]^{0.5}}\right\} \quad (5)$$

where S_i and M_i are the simulated and measured values, respectively, at site i. $\bar{M}$ and $\bar{S}$ are the means of the measured and simulated values, respectively. The range of R^2 is between 0 (no correlation) and 1 (perfect fit).

Ens is defined as:

$$Ens = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \quad (6)$$

where S_i and M_i are the simulated and measured values, respectively, at site i. The range of *Ens* lies between 1 (perfect fit) and $-\infty$. A negative value indicates that the mean value of the observed time series would have been a better predictor than the model.

5.2.7 Climate change impact assessment

This portion of the evaluation consists of climate data analysis to understand the projected changes in climate with respect to the baseline period (1986–2014) and the EPIC model simulation to assess the possible impacts on rice yield and SOC over the two long-term periods (2015–2045 and 2045–2075) under the A2 and B2 climate change scenarios. Management practices and parameters for the simulation periods were fixed as those of the baseline period for each site. Changes in key climate change indicators (temperature and precipitation), rice yield and SOC were analyzed by subtracting the output values under the climate change scenarios from the baseline values, and by estimating the percentage of change.

5.2.8 Statistical analysis

Statistical analyses of the data were performed using SPSS (version 20.0, USA). Mean and standard deviation (SD) values were used to represent rice yields and SOC for different areas and periods. Differences in rice yield and SOC between the baseline period (1986–2014) and the two long-term periods (2015–2045 and 2045–2075) under the A2 and B2 climate change scenarios were analyzed with *t*-tests and least significant difference (LSD) tests ($p < 0.05$). Simple linear regression analysis was used to find the relationships between measured and simulated values by fitting linear equations.

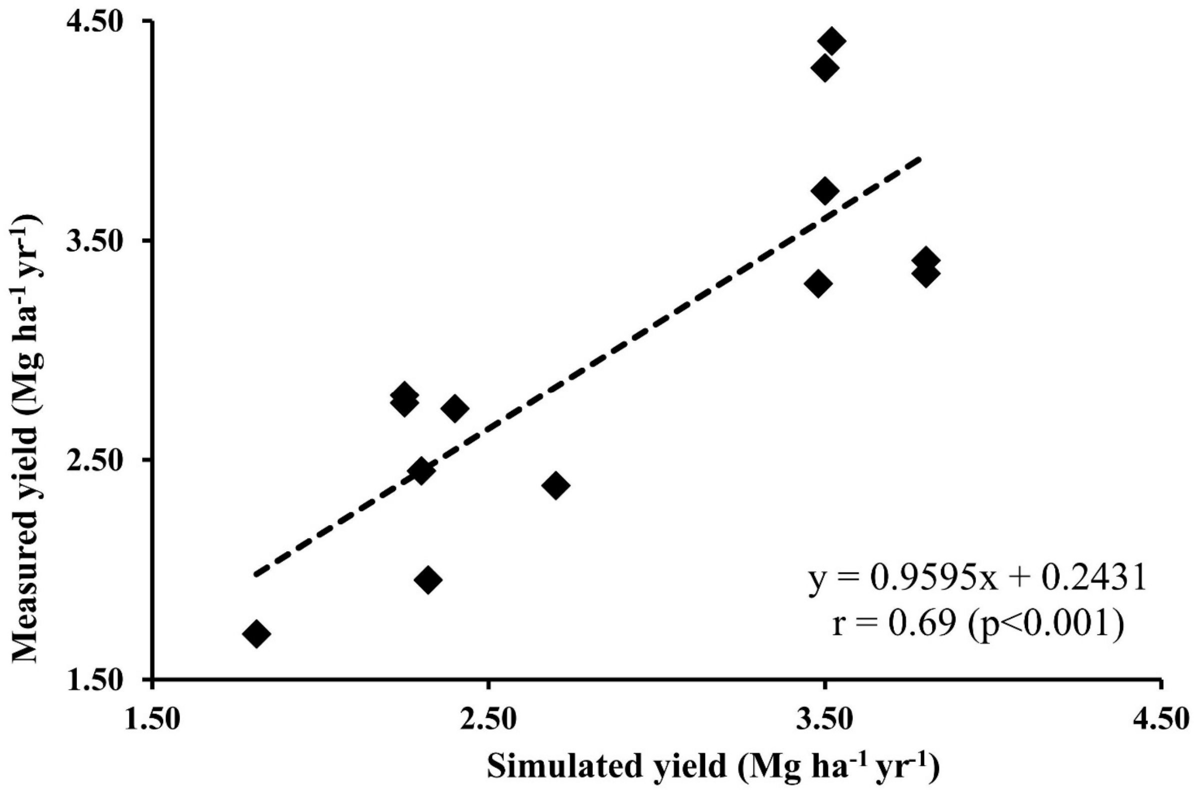
5.3 Results

5.3.1 Model calibration

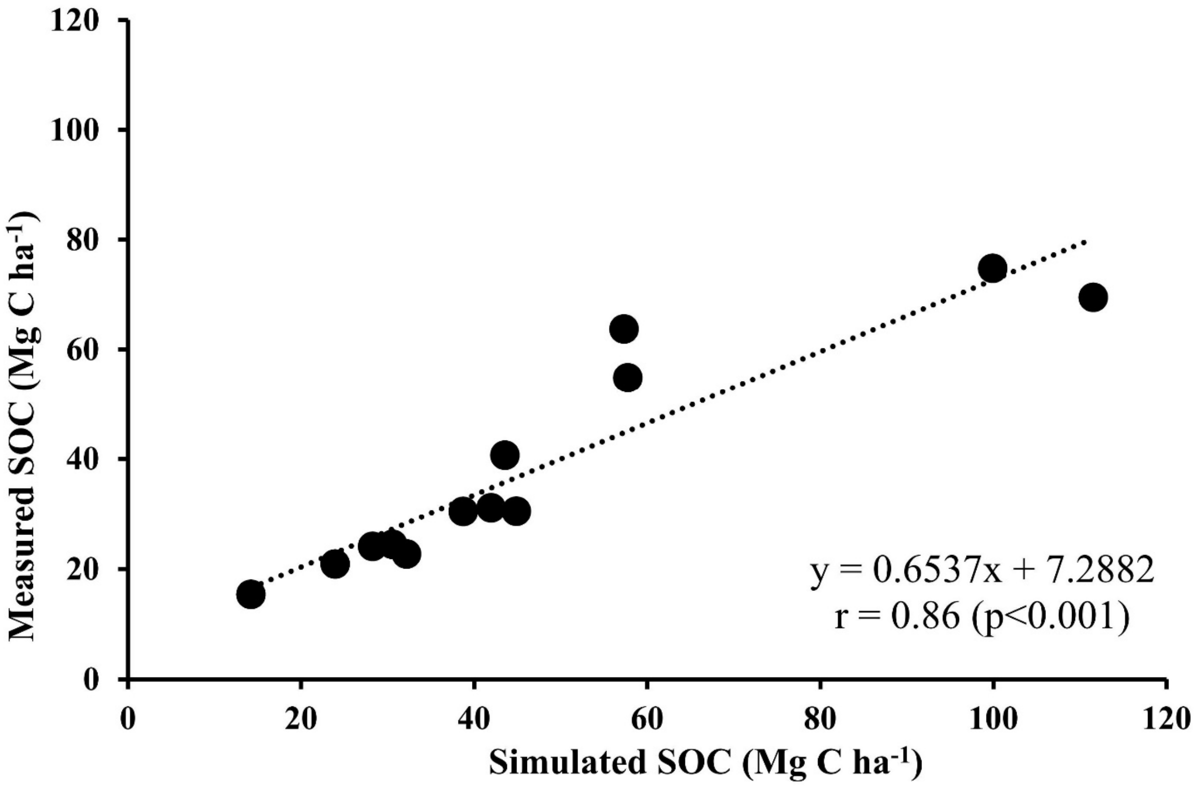
Model calibration was performed to compare the simulated rice yields and SOC with measured values for 13 sites. The results show that rice yields varied from 1.8 to 3.8 Mg ha^{-1} yr^{-1} and 1.7 to 4.4 Mg ha^{-1} yr^{-1} for the measured and simulated values, respectively. The average rice yields were 2.9 and 3.0 Mg ha^{-1} yr^{-1}, with standard deviations of 0.7 and 0.8 Mg ha^{-1} yr^{-1} for measured and simulated values, respectively (Figure 5-4 (a) and Table 5-5). The ranges of SOC values were 14.2–111.5 Mg C ha^{-1} and 15.4–74.8 Mg C ha^{-1} for the measured and simulated values, respectively. The average of SOC values were 48.1 and 38.9 Mg C ha^{-1}, with standard deviations of 28.5 and 20.1 Mg C ha^{-1}, for the measured and simulated values, respectively (Figure 5-4 (b) and Table 5-5). For the calibration procedure, the rice yield simulation R^2 and *Ens* values were 0.64 and 0.61, respectively, and the SOC R^2 and *Ens* values were 0.75 and 0.72, respectively. These findings indicate that the model was satisfactorily consistent with the results of visual evaluations. (Table 5-5).

For the sensitivity analysis, higher values indicate the higher sensitivity. These results shows that HI is the most sensitive parameter for rice yield, followed by WA, PHU, PARM(42), and PARM(3), with the sensitivity indices of 0.914, 0.673, 0.511, 0.226 and 0.245, respectively. These findings are consistent with those of Liu (2009), which indicate that HI is the most sensitive parameter for rice in Asia, followed by WA, PARM(42), PARM(3), and PHU, with sensitivity indices of 0.997, 0.485, 0.342, 0.334, and 0.318, respectively. This similarity is because the potential yields in the EPIC model are based on the accumulation of actual aboveground biomass and harvest indices, which are a function of the crop/variety and water stress in defined crop development stages (Gaiser et al., 2010). The highest sensitivity parameter for SOC is FHP, followed by PARM(47), PARM(51), PARM(55), PARM(54), PARM(45), PARM(52), PARM(56), PARM(53), and PARM(48), with sensitivity indices of 0.508, 0.075, 0.058, 0.027, 0.026, 0.024, 0.021, 0.019, 0.017, and 0.014, respectively. These results support those of Causarano et al. (2007), who reported that FHP was the most influential parameter for microbial biomass carbon (MBC) and particulate organic carbon (POC).

The highest sensitivity input variables for rice yield is maximum temperature, followed by solar radiation, precipitation, minimum temperature, N fertilizer, relative humidity, manure, rice residue, P_2O_5 and K_2O fertilizers, with sensitivity indices of 0.127, 0.118, 0.102, 0.086, 0.042, 0.030, 0.026, 0.007, 0.005, and 0.003, respectively. This is because the maximum and minimum temperature, and solar radiation are the main parameters to calculate harvest index and potential biomass for crop yields function in EPIC model. Meanwhile, precipitation is used to calculate the water stress factor, which control the variability of crop yields because crop yield increases or reductions are calculated through water stress-induced increases or reductions of the harvest index. In addition, our results show that manure is the most sensitive parameter for SOC, followed by rice residue, maximum temperature, minimum temperature, precipitation, N fertilizer, solar radiation, relative humidity, with sensitivity indices of 0.211, 0.182, 0.044, 0.025, 0.023, 0.005, 0.001, and 0.001, respectively, excepting P2O5 and K_2O fertilizers were no affect the variability of SOC. SOC is estimated by function that convert crop residue, root and organic amendment added to the soil that soil texture, moisture and temperature control on soil biological processes and turnover rate.



(a)



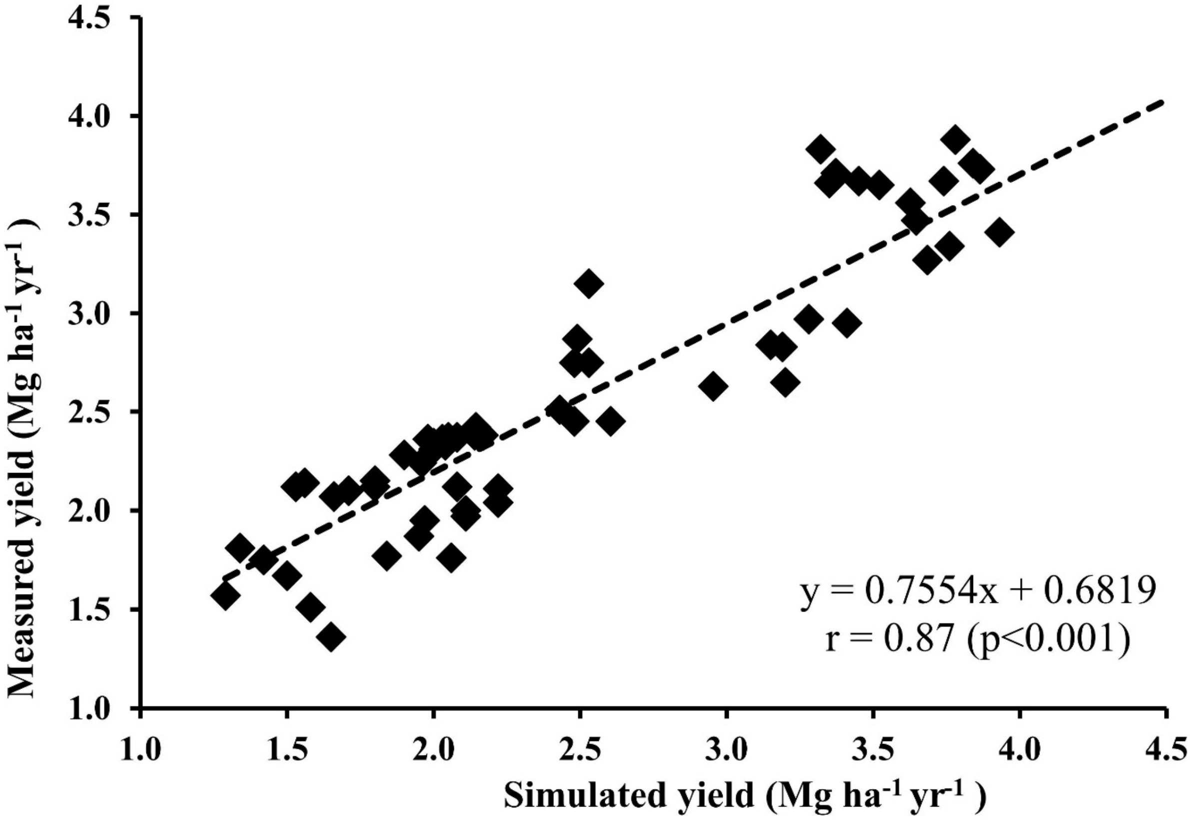
(b)

Figure 5-4 Result of calibration of the EPIC model for simulations of (a) rice yield and (b) SOC

5.3.2 Model validation

The measured and simulated rice yield and SOC values were distributed near the line $y = x$, and the r values were 0.87 and 0.93, respectively (Figure 5-5 (a) and (b)). The model performance of the validation procedure for rice yield was evaluated based on the R^2 and *Ens* values, which were 0.77 and 0.75, respectively. For SOC simulation, the statistical performance values were R^2 = 0.86 and *Ens* = 0.82, as shown in Table 5-5. Overall, the efficiency of the EPIC model predictions in this study is reasonable to good.

The simulated rice yields and SOC at all sites varied from 1.4 to 4.3 Mg ha^{-1} yr^{-1} and 5.6 to 118.4 Mg C ha^{-1}, respectively. The average simulated rice yield and SOC were 2.63 Mg ha^{-1} yr^{-1} and 38.0 Mg C ha^{-1}, with standard deviations of 0.7 Mg ha^{-1} yr^{-1} and 29.1 Mg C ha^{-1}, respectively. The range of measured rice yields and SOC were 1.3 to 4.9 Mg ha^{-1} yr^{-1} and 3.8 to 129.9 Mg C ha^{-1}, with average values of 2.59 Mg ha^{-1} yr^{-1} and 37.7 Mg C ha^{-1}, respectively (Table 5-5). These results indicate that the EPIC model tends to overestimate both rice yield and SOC, with average overestimations of 0.05 Mg ha^{-1} yr^{-1} and 0.28 Mg C ha^{-1}, respectively.



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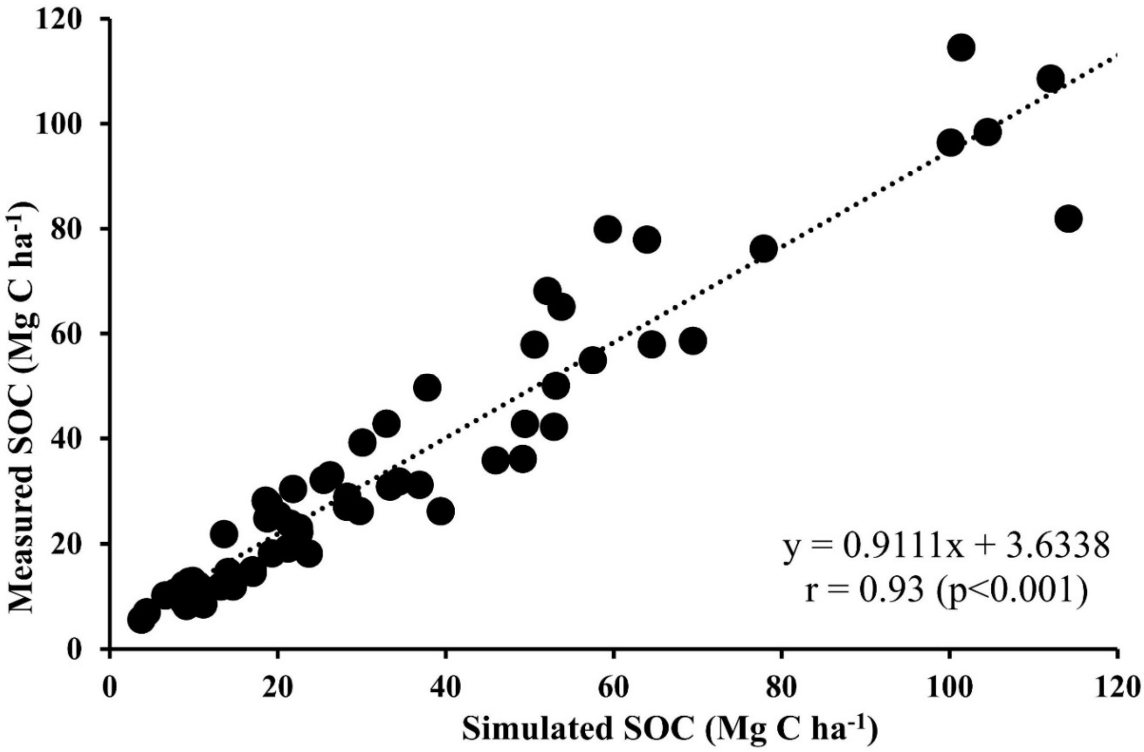


(b)

Figure 5-5 Comparison between measured and simulated values of (a) rice yield and (b) SOC

Table 5-5 Model evaluation statistics for the calibration and validation procedures

		Minimum	Maximum	Mean±SD	Model performance	
					R^2	*Ens*
Model calibration procedure (n = 13)						
Rice yield ($Mg\ ha^{-1}\ yr^{-1}$)	Measured	1.8	3.8	2.9±0.7	0.64	0.61
	Simulated	1.7	4.4	3.0±0.8		
SOC ($Mg\ C\ ha^{-1}$)	Measured	14.2	111.5	48.1±28.5	0.75	0.72
	Simulated	15.4	74.8	38.9±28.0		
Model validation procedure (all sites, n = 64)						
Rice yield ($Mg\ ha^{-1}\ yr^{-1}$)	Measured	1.3	4.9	2.59±0.9	0.77	0.75
	Simulated	1.4	4.3	2.63±0.7		
SOC ($Mg\ C\ ha^{-1}$)	Measured	3.8	129.9	37.7±32.1	0.86	0.82
	Simulated	5.6	118.4	38.0±29.1		

5.3.3 Changes in key climate change indicators

Analysis of key climate change indicator, including temperature and precipitation, are presented in Tables 5-4 and 5-5. The average baseline temperature in study area ranged from 21.6°C (January) to 29.4°C (April), with a mean annual temperature of 26.2°C. The mean annual temperatures in 2015–2045 and 2045–2075 were estimated to increase by +1.5°C and +2.2°C, respectively, under the A2 scenario, and by +1.1°C and +1.7°C, respectively, under the B2 scenario (Table 5-8). The monthly mean baseline precipitation in the study area ranged from 13.2 mm (January) to 572.7 mm (July), with the annual mean precipitation of 2339.3 mm. The annual mean precipitation in 2015–2045 and 2045–2075 increases by 2,948.1 mm and 3,103.4 mm, respectively, under the A2 scenario, and by 2,821.3 mm and 2,845.1 mm, respectively, under the B2 scenario. However, monthly mean precipitation in both scenarios and periods decreases in July to October relative to the baseline (Table 5-7). The monthly baseline precipitation ranges from 116.2 mm (October) to 572.7 mm (July), with a monthly mean precipitation of 357.3 mm. Under the A2 and B2 scenarios, the monthly mean precipitation decreases, with values of 357.7 mm and 360.2 mm, respectively (Table 5-7).

Throughout the next 60 years, the rate of annual temperature increase is estimated as +0.03 °C yr^{-1} under both the A2 and B2 scenarios, and the rate of annual precipitation increase is estimated as +0.42 and +0.08 mm yr^{-1}, respectively. The pattern of change in monthly precipitation reveals that the rainy season will occur one month earlier than baseline rainy season; the period of maximum precipitation will shift from July to June (Figure 5-6 (a)). Even the higher temperature will occur under the A2 and B2 scenarios, the pattern of change in monthly temperatures will be almost the same as those of the baseline (Figure 5-6 (b)).

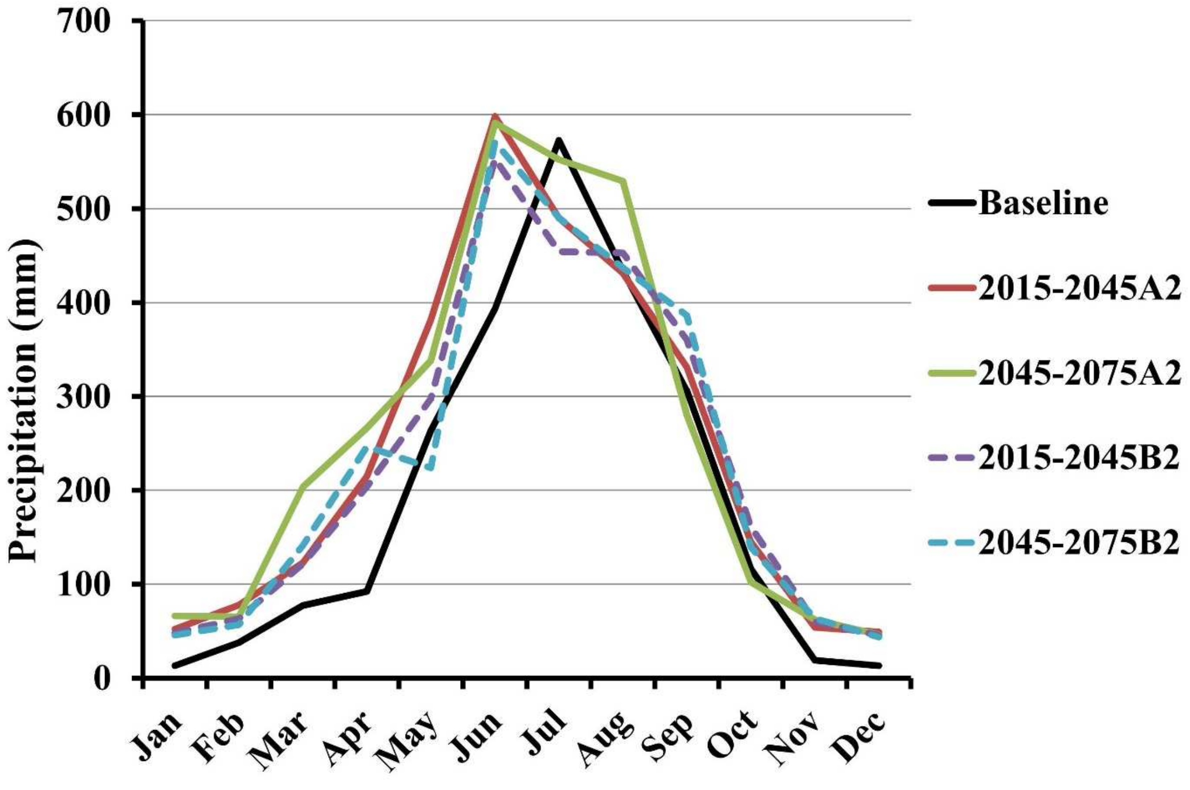
Table 5-6 Mean monthly temperature changes from the baseline under the A2 and B2 scenarios

Month	Baseline temperature (°C)	Mean monthly temperature change from baseline (°C)			
		A2 scenario		B2 scenario	
		2015-2045	2045-2075	2015-2045	2045-2075
Jan	21.6	1.2	1.7	0.6	1.1
Feb	25.4	1.0	1.8	0.6	1.3
Mar	27.6	3.1	3.9	2.4	3.4
Apr	29.4	2.5	3.0	2.6	2.9
May	29.1	2.5	3.1	1.9	2.6
Jun	27.9	0.6	1.4	1.0	1.3
Jul	27.7	0.5	1.4	0.4	0.3
Aug	26.8	2.0	2.4	0.6	1.4
Sep	26.8	1.0	1.6	0.8	1.8
Oct	25.6	2.0	2.5	1.5	2.3
Nov	24.4	0.4	1.4	0.5	1.2
Dec	21.7	1.1	2.0	0.7	1.2
Average	26.2	1.5	2.2	1.1	1.7

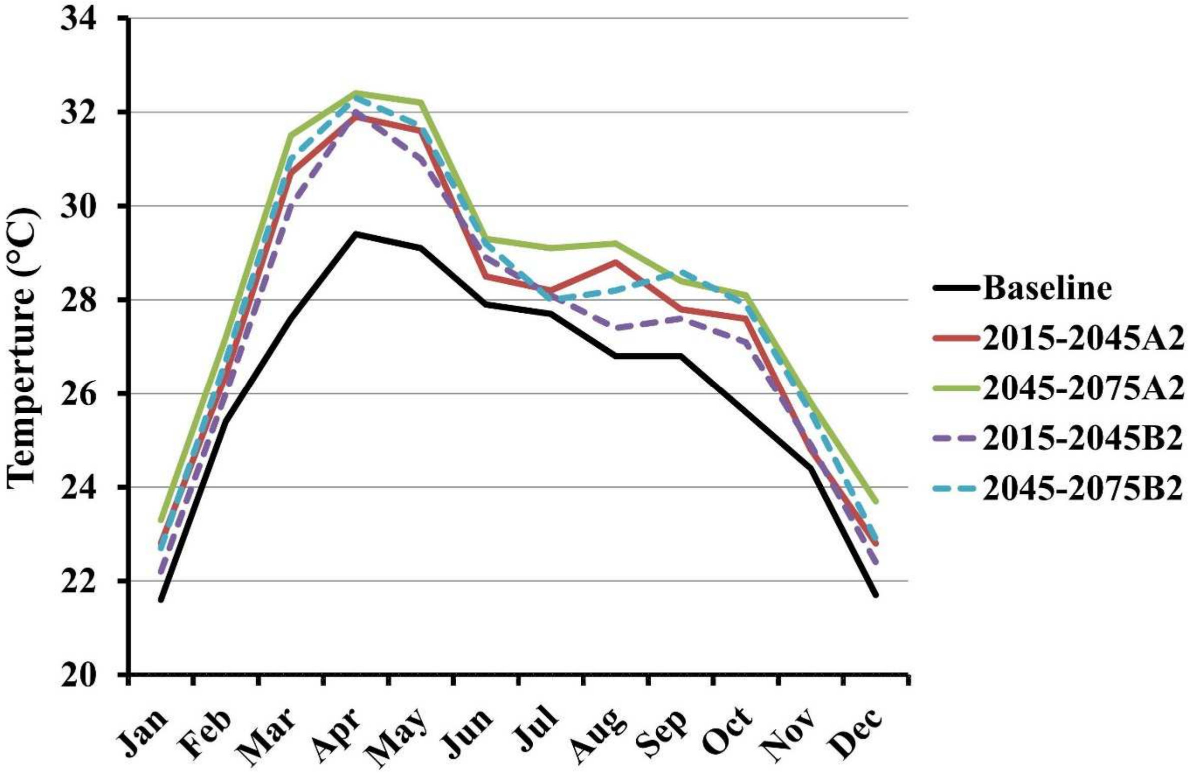
Table 5-7 Monthly percentage changes in precipitation from the baseline under the A2 and B2 scenarios

Month	Baseline precipitation (mm)	Amount of precipitation under climate change scenarios (mm)			
		A2 scenario		B2 scenario	
		2015-2045	2045-2075	2015-2045	2045-2075
Jan	13.2	52.0 (+2.9-fold)	66.2 (+4.0-fold)	48.1 (+2.6-fold)	45.8 (+2.5-fold)
Feb	37.8	77.7 (+1.1-fold)	65.4 (+0.7-fold)	63.2 (+0.7-fold)	56.8 (+0.5-fold)
Mar	77.4	122.8 (+0.6-fold)	203.6 (+1.6-fold)	121.6 (+0.6-fold)	141.3 (+0.8-fold)
Apr	92.4	214.9 (+1.3-fold)	266.4 (+1.9-fold)	203.7 (+1.2-fold)	246.5 (+1.7-fold)
May	263.4	381.9 (+0.4-fold)	338.3 (+0.3-fold)	297.3 (+0.1-fold)	223.7 (-0.15-fold)
Jun	393.5	598.1 (+0.5-fold)	591.1 (+0.5-fold)	553.0 (+0.4-fold)	570.8 (+0.5-fold)
Jul	572.7	489.9 (-0.14-fold)	552.1 (-0.04-fold)	454.2 (-0.21-fold)	490.1 (-0.14-fold)
Aug	434.1	431.3 (-0.01-fold)	529.2 (+0.2-fold)	453 (+0.04-fold)	437.1 (+0.01-fold)
Sep	306.4	331.5 (+0.1-fold)	280.5 (-0.08-fold)	360.6 (+0.2-fold)	386.5 (+0.3-fold)
Oct	116.2	144.8 (+0.2-fold)	102.1 (-0.12-fold)	160.9 (+0.4-fold)	139.3 (+0.2-fold)
Nov	18.9	54.1 (+1.9-fold)	62.2 (+2.3-fold)	60.1 (+2.2-fold)	63.5 (+2.4-fold)
Dec	13.3	49.1 (+2.7-fold)	46.3 (+2.5-fold)	45.6 (+2.4-fold)	43.7 (+2.3-fold)
Sum	2339.3	2948.1	3103.4	2821.3	2845.1

The number in the parenthesis indicates changing of precipitation from baseline. "+"indicates increasing of precipitation, "-"indicates decreasing of precipitation.



(a)



(b)

Figure 5-6 Monthly average values of (a) precipitation and (b) temperature for the baseline (1986–2014) and the A2 and B2 scenarios for 2015–2045 and 2045–2075

5.3.4 Rice yield simulation under climate change scenarios

Overall, rice yields in 2015–2045 and 2045–2075 under the A2 and B2 scenarios increased significantly compared to baseline yield (p < 0.01) (Table 5-8). The simulation of rice yields in each site is detailed in Appendix Tables A-3 and A-4 for irrigated and rain-fed areas, respectively. The average baseline rice yield was 2.6 Mg ha^{-1} yr^{-1}. The average rice yields in 2015–2045 and 2045–2075 are estimated to increase by +70.8% and +97.3%, respectively, under the A2 scenario, and by +30.5% and +52.9%, respectively, under the B2 scenario. Higher rates of increase are found in rain-fed areas than in irrigated areas in both periods and under both scenarios (Table 5-8). However, the average rice yields under the A2 scenario were higher than those under the B2 scenario for both periods. Both scenarios may evoke greater benefits for rice grown in rain-fed areas than in irrigated areas because increasing amounts of precipitation can reduce water stress in rain-fed areas by increasing soil available water and enhancing crop growth, which are accompanied by higher yields (Agele et al., 2011). Furthermore, as indicated by Salvador Sanchis et al. (2008), soil available water and distribution may respond rapidly to climate change, especially drought events; therefore, enhancing water infiltration and available water in soil may help mitigate the impacts of severe drought events in rain-fed areas.

5.3.5 SOC simulation under climate change scenarios

Under both the A2 and B2 scenarios, SOC decreased significantly in 2015–2035 and 2045–2075 compared to baseline SOC ($p < 0.01$ and 0.05) (Table 5-9). The simulation of SOC in each site is detailed in Appendix Tables A-3 and A-4 for irrigated and rain-fed areas, respectively. The average baseline SOC was 38.0 Mg C ha^{-1}. The average SOC in 2015–2045 and 2045–2075 was estimated to decrease by 34.3% and 47.6%, respectively, under the A2 scenario, and by 26.3% and 29.5%, respectively, under the B2 scenario. Under both the A2 and B2 scenarios, the results show that the decreases of SOC in rain-fed areas were higher than those in irrigated areas compared to the baseline. This discrepancy is because of higher rates of SOC decomposition and amounts of C released as CO_2 in red-fed areas relative to irrigated areas. Conversely, when fields are flooded, decomposition of organic material depletes oxygen in the soil and flood water, which results in poorly aerated soils (Rath et al., 2000), and leads to slower decomposition rates and greater SOC sequestration (Chen et al., 2016).

Table 5-8 Simulated rice yields of 64 sites under the A2 and B2 scenarios and the baseline (Mean ± SD)

		Rice yield (Mg ha^{-1} yr^{-1})			Rice yield change (Mg ha^{-1} yr^{-1})			Change in rice yield from baseline (%)		
		Irrigated	Rain-fed	All sites	Irrigated	Rain-fed	All sites	Irrigated	Rain-fed	All sites
Baseline		2.9±1.1	2.4±0.7	2.6±0.9	-	-	-	-	-	-
A2 scenario	2015-2045	4.2±0.9	4.1±0.9	4.1±0.9**	1.3±0.7	1.7±0.8	1.6±0.8	55.9±40.7	79.7±43.7	70.8±43.8
	2045-2075	4.9±1.2	4.8±1.1	4.8±1.0**	2.0±0.6	2.4±0.6	2.2±0.6	78.5±39.0	108.5±42.0	97.3±43.1
B2 Scenario	2015-2045	3.2±1.0	3.2±0.8	3.2±0.9**	0.3±0.5	0.9±0.6	0.7±0.6	13.9±20.0	40.4±29.0	30.5±28.9
	2045-2075	3.7±1.0	3.8±0.9	3.7±0.9**	0.7±0.5	1.4±0.6	1.2±0.7	31.9±24.5	65.4±32.6	52.9±33.8

** = Significant at 1%, between the baseline and the two long-term periods (2015–2045 and 2045–2075) under the A2 and B2 climate change scenarios.

Table 5-9 Simulated SOC of 64 sites under the A2 and B2 scenarios and the baseline (Mean ± SD)

		SOC (Mg C ha^{-1} yr^{-1})			SOC change (Mg C ha^{-1} yr^{-1})			Change in SOC from BL (%)		
		Irrigated	Rain-fed	All sites	Irrigated	Rain-fed	All sites	Irrigated	Rain-fed	All sites
Baseline		43.5±33.4	34.7±28.1	38.0±30.3	-	-	-	-	-	-
A2 scenario	2015-2045	36.5±34.5	25.1±25.0	29.4±29.2**	-7.0±5.8	-9.6±4.8	-8.6±5.3	-29.2±26.0	-37.3±18.6	-34.3±21.8
	2045-2075	34.8±36.6	20.7±23.7	26.0±29.8**	-8.7±8.0	-13.9±6.7	-12.0±7.6	-37.9±33.8	-53.5±23.6	-47.6±28.6
B2 Scenario	2015-2045	38.0±34.6	27.4±25.4	31.4±29.4*	-5.5±5.9	-7.2±4.4	-6.6±5.0	-23.4±22.2	-28.0±16.7	-26.3±18.9
	2045-2075	37.5±35.2	26.8±25.7	30.8±29.8**	-6.0±6.4	-7.8±4.4	-7.2±5.3	-26.8±26.6	-31.1±19.2	-29.5±22.2

*, ** = Significant at 5% and 1%, between the baseline and the two long-term periods (2015–2045 and 2045–2075) under the A2 and B2 climate change scenarios.

5.4 Discussion

5.4.1 Potential of the EPIC model to simulate rice yields and SOC

Overall, the validation and reliability of the EPIC model are acceptable and indicate good predictive capability, as indicated by the values of $R^2 > 0.50$ and $Ens > 0.60$ for both rice yield and SOC (Table 5-5). In this study, overestimation by the EPIC model was found for both rice yield and SOC (Table 5-5). These results support those of Guerra et al. (2004), who pointed out that this model tends to overestimate at low yields, especially under water-stress conditions. Similarly, Izaurralde et al. (2006) reported that the EPIC model overpredicts at low SOC values and underpredicts at high SOC values. Gaiser et al. (2010) reported that the performance of the EPIC model was best for slightly acidic soils ($R^2 = 0.85$) and poorest for strongly acidic soils with high aluminum saturation ($R^2 = 0.40$). In particular, when extremely acidic soils were associated with semi-arid conditions and with high precipitation variability, then the model strongly overestimated crop yields. These findings support the overestimation of the EPIC model detected in our study area, where low pH values (3.86–6.66) are measured in surface soils to 40 cm depth (Table 5-1) and precipitation is highly variable for the whole year (Table 5-7).

5.4.2 Climate change impacts on rice productivity

The A2 and B2 scenarios show temperatures and precipitation increasing over the next 60 years (Tables 5-4 and 5-5). The A2 scenario shows higher average temperatures and precipitation than does the B2 scenario. Downing (1992), Rosenzweig and Iglesis (1994), Furuya and Koyama (2005), and Aggarwal et al. (2010) also reported that both the maximum and minimum temperatures, as well as average temperatures, in Asia are increasing, and average precipitation may also increase. These studies suggest that future climate changes under both the A2 and B2 scenarios will follow the same direction, but the A2 scenario is likely to induce more severe changes than the B2 scenario. However, research by Erda et al. (2004; 2005) using the PRECIS model for China showed that rice yields are higher under the A2 scenario than under the B2 scenario. This finding is because the different levels of CO_2 directly affect the rice yields. The continuously increasing levels of CO_2 also cause yields and biomass to increase by 5−15%. Rice yields at 550 ppm CO_2 are therefore greater than those at 450 ppm CO_2. Increasing levels of CO_2 may cause negative effects on the germination of rice seeds and decrease stomatal aperture sizes, but may enhance photosynthetic activity (Mott, 1988). Similarly, Lin et al. (2005) used the PRECIS regional climate model and the CERES crop model to analyze the impacts of climate change and CO_2 fertilization on crop productivity for both the A2 and B2 scenarios and found highly variable results for wheat, corn, and rice depending on the scenario and irrigation practices uses. Shen et al. (2011) showed that irrigated rice generally has higher rice yields in the middle and lower reaches of the Yangtze River valley compared to the rain-fed rice because irrigated rice is less affected by climate change, and that irrigation can relieve water stress for rice growing in the northern region of the Yangtze River valley. Their results show that under irrigation conditions, rice growth is not influenced by precipitation, whereas rain-fed rice is susceptible to the temporal and spatial variation of precipitation. These findings support our results that indicate that future climate change scenarios could have positive impacts on rice yield in Northeast Thailand in the next 60 years, especially in rain-fed areas, because rice yields in the study area vary depending on the distribution of precipitation during the growing season (Table 5-8). We hypothesize that increasing temperature and precipitation results in accelerated organic matter decomposition rates and rapid release of nutrients into the soil (Brady and Weil, 1999), which may increase N availability (Mack et al. 2004; Schaeffer et al., 2013) and lead to increased yields in rain-fed areas (Kant et al., 2012). Rising temperatures are also expected to enhance soil C availability by increasing plant primary productivity and allocation from plants to the soil (Xu et al., 2013);

thus, high N availability may also benefit from increasing plant productivity. In addition, rising precipitation under future climate change scenarios may lead to increased CO_2 fertilization and atmospheric N deposition, which may support high plant productivity and organic matter input to the soil and consequently increase SOM (French et al., 2009).

Additionally, there are climatic parameters with effects on rain-fed crop growth and yields that may change inter-annual variability in yield more than they affect long-term yields, depending on the stress tolerance of different cultivars. In particular, any drought effects and inhibition of photosynthesis during grain filling have strong effects on grain yields (Boyer et al., 1976). This effect is because under water deficiency, cell elongation in higher plants can be inhibited by interruption of water flow from the xylem to the surrounding elongating cells, which results in reduced plant height, leaf area and crop growth (Nonami, 1998; Hussain et al., 2008). Reduced water availability under drought conditions typically results in more limited nutrient availability and uptake in crop plants (McWilliams, 2003). Naklang et al. (2006) and Suriyakup et al. (2007) suggested that some rice varieties with higher potential yields may be suitable for situations in which optimal water and nutrient management can be assured. Therefore, other relevant factors must be considered for the rice yield forecasts in this study, such as the appropriate variety of rice, irrigation system development, and especially nutrient management, to properly integrate these factors with related practices and maintain nutrient use efficiency. Nutrients can generally be obtained from manure, fertilizers, crop residues, water, atmospheric deposition, and nitrogen fixation by legumes. Farmers who adopt nutrient management practices are likely to have crops with greater resilience to the effects of climate change on crop nutrients because they are already engaged in an adaptive management practices.

5.4.3 Climate change impacts on SOC

Changes in SOC sequestration can influence crops in two main ways: 1) through affecting photosynthesis and respiration in plants, which in turn affects the quantities of residues in soil; and 2) through changing the decay rates of these residues in soil (Rey et al., 2006; Plante et al., 2011). Several studies have implicated temperature and precipitation as primary controls on SOC stability; these parameters alter the quality and quantity of litter input into the soil, as well as soil physico-chemical characteristics (Trumbore et al., 1996; Bird et al., 2002; Garten and Hanson, 2006; Dai and Huang, 2006). In this study, both the A2 and B2 scenarios show statistically significant decreases in SOC for all sites relative to the baseline. Much greater decreases in SOC are estimated under the A2 scenario than under the B2 scenario (Table 5-9). This difference is because temperatures and precipitation under the A2 scenario rose much higher than those under the B2 scenario (Tables 5-4 and 5-5), which results in increased C release and a decreased C reservoir. Our findings are consistent with those of previous studies that reported that a rise in precipitation and temperature enhances SOC decomposition because of increased microbial activity (Alvarez and Alvarez, 2001; Friedlingstein et al., 2001; Zhang et al., 2004; Smith et al., 2005). Conant et al. (2008) also indicated that the faster SOC turnover rates associated with higher temperatures may result in the loss of significant amounts of the C stored in agricultural soils.

5.4.4 Farming practice adaptations

The results of our study confirm that climate change will impact rice yields positively, which will benefit farmers in this region. However, climate change will cause decreases in SOC sequestration and lead to increased CO_2 release into the atmosphere. Furthermore, other yield limiting factors associated with climate change were not considered in this study. For example, in northeastern Thailand, diseases and pest insect damage typically increase when droughts occur and temperatures increase. Another problem not assessed herein is increased heavy precipitation; climate change may lead to flash floods, which destroy rice fields and cause nutrient loss. Therefore, farmers should be prepared for adaptation not only for crop management, but also for other forms of risk mitigation. Regarding adaptation options within crop management practices for farmers, our study supports starting early planting in June, as well as faster harvesting, because the timing of maximum precipitation will shift from July to June, (Figure 5-5). Meanwhile, optimal fertilization, manuring, and residue incorporation practices should be carefully considered to mitigate greenhouse gas emissions and more effectively maintain SOC stock.

5.5 Conclusions

The EPIC model performance was satisfactory and acceptable; the model therefore provided good predictions of rice yields and changes in SOC under future climate conditions in rice paddy fields in Northeast Thailand. The average temperatures and precipitation in both the A2 and B2 scenarios will increase over the next 60 years relative to the baseline. The pattern of change in monthly precipitation indicates that the rainy season will occur one month earlier than under baseline conditions. Climate change will impact rice yields positively, which will benefit farmers, especially in rain-fed areas. However, climate change will cause decreases in SOC sequestration. These changes in yields and SOC will occur because rising temperatures and precipitation levels will enhance potential crop growth and accelerate SOC decomposition, which may increase N availability. Based on these predictions, farmers should be prepared to take adaptation and mitigation measures. Our study supports the adaptation option of starting early planting in June, as well as harvesting faster, because the maximum precipitation period will shift from July to June.

Chapter 6

General discussion

Climate changes impacts and agricultural management practices are among the most crucial factors to take into consideration when it comes to enhancing agricultural productivity and optimizing farming practices. In terms of agricultural management practice, the focus should be placed on SOC dynamics as a change in SOC often results from changes in climatic conditions such as precipitation and temperature due to the function of soil C sequestration as primary production and OM decomposition (Grace et al., 2006; Hutchinson et al., 2007). Under anaerobic conditions, relatively low decomposition rate is often observed with high organic materials input into paddy soil (Huang et al., 2015). Several studies have demonstrated the essential role of soil carbon sequestration against climate change (Bhattacharyya et al., 2013; Majumdar et al. 2008). Indeed, the effects of climate factors and management practices on SOC are often intertwined, making it difficult to identify the main drivers at the local scale. This study is the first detailed local investigation and analysis of how farmers' actual management practices influence SOC and rice yield. Our knowledge may potentially contribute to the more widespread application of suitable agricultural management practices in paddy fields across Thailand, as well as the capacity enhancement of the soils and the mitigation of Thailand's increasing CO_2 emissions.

6.1 Strategies for enhancing SOC and rice yield

This study revealed that the SOC sequestration can be increased by suitable management practices which combine fertilizer and manure application and avoid burning rice residues. The increased rate of fertilizer application linearly enabled increasing in SOC levels residue accumulation by enhancing residue accumulation (Singh and Lal, 2005). Our investigations are consistent with previous studies (Singh and Lal, 2005; Kong et al., 2006), in which the addition of fertilizer input was proved to positively affect SOC sequestration. Nevertheless, adverse effects on N_2O emissions are often observed as a result of an increase in mineral N fertilizer rate that allows C sequestration to increase (Desjardins et al., 2001). In addition, it was found that N leaching from the first layer of soils often increased linearly when the N fertilizer application rate rose up (Peinetti et al., 2008). It is, therefore, important that an optimal rate of N fertilizer application should be set with considering the environmental protection in the C sequestration management. Traditionally, farmyard manure is usually put back into the field with an aim to increase plant growth and crop yield by farmers in the northeastern region of Thailand. However, the rapid economy development and short-term profits gain cause increasing of the synthetic fertilizers utilization instead of farmyard manures.

In this study, most of the rice residues except for the root biomass are excluded. Keeping rice straw makes it possible for soil structure to improve through various mechanisms: (i) soil aggregation is enhanced as OM is added to top layers of the soil, (ii) soil aggregates are protected from raindrop impact, and (iii) soil is protected from compaction as a result of raindrop impact (Six et al., 2006; Jacobs et al., 2009; Verhulst et al., 2010). Soil aggregates can also protect SOM from decomposition as it forms tight organo-mineral complexes to prevent microorganisms from accessing the OM (Six et al., 2000).

In addition, there has been another suggestion which is the conversion of the rice straw into biochar and returned to the soil in stand of open burning on the rice field. Biochar has been estimated that the C-rich charred remains from heating biomass in no oxygen conditions. Nevertheless, while rice straw is burnt in the open it is exposed to plenty of oxygen therefore the combination of the C from the biomass and the oxygen in the air releases CO_2 into the atmosphere. That means during the burning phase without oxygen the C in the biomass largely remains intact (Lehmann et al., 2011). Therefore, the amount of GHG released into the atmosphere can be reduced by the creation of biochar rather than the ash of open burnt rice residues and the carbon can remain in the soil for hundreds of thousands of years (Krull et al, 2009; Wu et al, 2012). Given the findings, the best strategy to increase SOC content, and enhance agricultural productivity and sustainability in the northeastern region of Thailand is to combine the application of farm-generated organic manure with inorganic fertilizers.

6.2 Soil carbon sequestration as a strategy to GHG emissions reduction

As suggested by Thailand's Second National Communication (SNC) on GHG reporting, Thailand's total GHG emissions in 2000 was 229.08 $TgCO_2eq$. The energy sector accounted for the biggest part accounting for 159.39 $TgCO_2e$ or 69.6%, which is more than the agricultural sector accounting for 51.88 $TgCO_2e$ or 22.6%, threefold less than the energy sector. Major emission from the agricultural sector was CH_4, which was largely attributed to the rice farming that released 29.94 $TgCO_2e$ of GHGs, accounting for 57.7% of the total emissions in agricultural sector and 13.07% of the whole country's emissions. However, rice farming contributed to 1.5% of 2000 global GHG emissions (41,755 $TgCO_2eq$), 77% of which were attributed to the energy and industrial sectors (ONEP, 2010). Accordingly, it is important that GHG emissions should be reduced in quantity from agricultural soils in order to sustain the soil carbon (C) storage.

Carbon sequestration in tropical soils has potential for mitigating global warming and increasing agricultural productivity (Pathak et al., 2011). Soil C sequestration occurs when the amount of C input into the land is larger than that emitted to the atmosphere. It has been estimated that 89% of the total mitigation potential of agricultural GHG emission, followed by 9% and 2% for CH_4 and N_2O emission reduction from soils, respectively (Smith et al., 2007). Though tropical regions face limitation of soil carbon sequestration because of high temperatures, reasonable quantities of C can still be sequestered through an adoption of appropriate management practices, especially in high precipitation regions. This study revealed that burned rice residues was the main factor determining the GHGI in this area. The management practices, where the net GWP and GHGI were low, were no burned rice residues, incorporation of manure and chemical fertilizer, or application of only chemical fertilizer. These were in line with the previous studies that rice residue open burning is widely practiced in Thailand to remove residue and control weeds due to saving time and costs (Garivait, 2005; Suramaythangkoor and Gheewala, 2008; Gadde et al., 2009).

Although this study have included the SOC content at local-scale data in the estimation of GHGI which is usually limited data available due to high uncertainties at the large-scale data (Wang et al., 2015), the analysis focuses on emissions only within the rice field which they are not full lifecycle analysis. It should be conducted in the further research to improve the GHGI assessment and realize the mitigation potential. Moreover, accurate estimates are required for the rate of SOC sequestration according to change in management practices. There are very few long term trials in Thailand in which SOC have been monitored as a function of management practices. Therefore, this is an urgent necessary to obtain this type of data to identify management practices with more potentiality in SOC sequestration.

6.3 Adaptation responses to climate change

Various studies report a rice yield change and SOC with climate variability. Notwithstanding, the precise effect on yield is based on the temperature at a specific site in relation to critical temperatures at different growth stages (De Datta 1981). As this study, rice yield and SOC were evaluated the possible impact of climate change using local-scale data. The climate change signal will impact the rice yield in positive way, which will make more benefit for farmers, especially in rain-fed areas. There are two main reasons to explain this phenomena: i) Increasing amount of precipitation reduce the water stress factor by enhancing the soil available water and nutrient from precipitation (i.e. NH_4, NO_3), resulting rice yield increased, and ii) Increasing atmospheric concentration of CO_2 leads to CO_2 fertilization increase. Adams et al. (1990) reported a 10 to 50% increase in dry matter with doubling of CO_2 in most species of crops when all other factors remain constant. Warrick et al. (1986) reported that C3 crops (such as wheat, rice, and soybean) saw an increase of 10-50% in growth and yield while C4 crops (such as maize and sugar cane) saw an increase of 0-10% with the doubling of CO_2 concentration. Our result supports the adaptation option of beginning early planting in June, as well as harvesting faster, because the maximum precipitation period will shift from July to June. It should also be noted that, in fact, some autonomous adaptations will be unavoidably made even if they are not planned ahead of time, whereas the crop models usually reach their results based on an assumption that the farming practices will remain unchanged.

On the other hand, higher temperature and precipitation lead to higher OM decomposition rates (Davidson et al., 2000; Reichstein et al., 2003), which was consistent with our finding. Vleeshouwers and Verhagen (2002) demonstrated that the temperature of 1˚C increase generates 0.05 Mg C ha^{-1} yr^{-1} in SOC stocks decrease. Comparing with well-aerated soils, decomposition of OM occurs more slowly in poorly aerated soils, where oxygen is limiting or absent (Batidzirai et al., 2016). This finding was in line with our study that the decreasing of SOC in rain-fed areas was higher than irrigated areas. Therefore, our finding do support focusing on irrigation management because of the significance of irrigation in buffering the impact of the dry spells and precipitation seasonality, and also enhance SOC sequestration.

However, nutrient stress remains a mostly unclear link in understanding how climate change will affect crop yields, requiring better integration of management practices with crop models to evaluate the crop response with mineral nutrient supply. It is likely that increasing of temperature and precipitation will accelerate many microbial processes in the soil, with consequences for the C and N cycles, especially N loss.

Chapter 7

Summary and Conclusion

Soil management practices that alter the SOC content is important for the sustainable management to enhance rice yield with low GHGI. Especially, sandy soils are usually dominant in tropical monsoon regions, due to the high weathering potential associated with high temperatures and precipitation. Not only the pertinent management practices (i.e. combination of manure, rice residues, and chemical fertilizers), but climate change and rising atmospheric CO_2 can also effect on rice yield and SOC sequestration. Although the soils have the potential to mitigate increasing CO_2 concentrations through C sequestration, land misuse and soil mismanagement have caused depletion of SOC. Therefore, the goal of this study is to examine the influences of land management practices, and climate change attributes on rice yield and SOC in Northeast Thailand.

To do so, we performed three specific objectives as following details. Firstly, investigation the distribution of rice yield and SOC content under different land management practices, and analyzes the relationship between rice yield and SOC with pertinent management practices (manure and fertilizer applications). Secondly, estimation the effect of land management practices on net GWP and GHGI. Finally, evaluation the reliability of EPIC model calibration and validation processes based on local scale data, and evaluate the possible impact of climate change on rice yield and SOC sequestration.

7.1 Practices sustaining soil organic matter and rice yield

Rice yield and SOC content were investigated the distribution under different land management practices, and analyzed the relationship between rice yield and SOC with pertinent management practices (manure and fertilizer applications). The mean rice yield of the whole crop year and SOC were 2.93 Mg ha^{-1} and 47.09 Mg C ha^{-1}, respectively, in the irrigated areas, and were 2.38 Mg ha^{-1} and 32.08 Mg C ha^{-1} in the rain-fed areas. Significantly higher values were obtained in the irrigated areas ($p < 0.05$). There was a significant positive correlation between rice yield and SOC in both the irrigated areas ($R^2 = 0.72$, $p < 0.01$) and the rain-fed areas ($R^2 = 0.85$, $p < 0.01$). In both irrigated and rain-fed areas, manure should be applied every year, with an optimal application rate of N, P, and K fertilizers being selected. The combination of manure, fertilizer, and increasing irrigation facilities the maintenance of SOC levels and substantially increases rice yields.

7.2 Practices for reducing greenhouse gas emissions from rice production

The effects of land management practices on GWP and GHGI from rice production in Thailand were investigated. Of the 13 study sites where SOC was estimated by the Land Development Department. Soil samples were collected in 2004 again in 2014 at these same sites to estimate the SOCSR from 2004 to 2014. Surveys were conducted at each sampling site to record the rice yield and management practices. The CO_2, CH_4, and N_2O emissions, net GWP and GHGI associated with the management practices were calculated. Mean rice yield and SOCSR were 3307 kg ha^{-1} yr^{-1} and 1173 kg C ha^{-1} yr^{-1}, respectively. The net GWP varied across sites, from 819 to 5170 kg CO_2eq ha^{-1} yr^{-1}, with an average value of 3090 kg CO_2eq ha^{-1} yr^{-1}. GHGI ranged from 0.31 to 1.68 kg CO_2eq kg^{-1} yield, with an average value of 0.97 kg CO_2eq kg^{-1} yield. Our findings revealed that the amount of potassium (potash, K_2O) fertilizer application rate is the most significant factor explaining rice yield and SOCSR. The burning of rice residues in the field was the main factor determining GHGI in this area. An effective way to reduce GHG emissions and contribute to sustainable rice production for food security with low GHGI and high productivity is avoiding the burning of rice residues.

7.3 Using EPIC model to predict local scale impact of climate change on rice yield and soil organic carbon sequestration

The EPIC model was calibrated using measured values of rice yield, SOC, and management practice of 13 sites in 2004. The validation process employed the measured values of all sites (64 sites) over 5 years (2010-2014) for rice yield, and in 2014 for SOC and management practice. Using the properly calibrated parameter values, simulation was conducted two long-term periods (2015-2045 and 2045-2075) under A2 (medium high emissions) and B2 (medium low emissions) scenarios, which proposed by Southeast Asia START Regional Centre, while baseline period (1986-2014) was from the Thai Meteorological Department. The model performance of calibration revealed that the rice yield simulation with R^2 and *Ens* values of 0.64 and 0.61, respectively, while SOC was R^2 of 0.75, and *Ens* of 0.72. The model validation demonstrates that the model satisfactorily confirmed the fairly good impression of the visual evaluation of both rice yield (R^2 of 0.77, and *Ens* of 0.75) and SOC (R^2 of 0.86, and *Ens* of 0.82). Higher averages of temperature and precipitation under A2 scenario in the study area will increase rice yield higher than that of B2 scenario, especially in rain-fed areas. Conversely, climate change will cause the decreasing of SOC sequestration due to a rise in temperature and precipitation accelerate the SOC decomposition that may increase nitrogen availability to the soil, leading to increase yield of rain-fed areas. Our study supports the adaptation option of starting the early planting in June, and faster harvesting because the maximum precipitation period will shift from July to June.

7.4 Conclusion

This study clearly showed strong correlation between rice yield and SOC, and the management practices of manure, residue and fertilizer applications increased rice yield and SOC. Burning residue was the main cause to increase GWP in rice paddy area. Increase of temperature and precipitation with climate change may increase rice yield, but may decrease SOC. Increase of temperature and precipitation stimulates microbial activities increasing the rate of SOC decomposition, and high amount of precipitation increases soil erosion reducing SOC. Furthermore, sandy soil, which dominates in this study area, is easy to decrease SOC due to low clay content to protect the SOC from microbial decomposition. Therefore, management practices of manure and residue applications, avoiding burning crop residues and balancing nutrients by chemical fertilizer application will be more important for sustainable rice production in Northeast Thailand.

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Appendix

Table A-1 Main management practices, rice yield, and SOC in irrigated areas (n = 24)

Site No.	Rice season	Rice yield (Mg ha^{-1} yr^{-1})	SOC (Mg C ha^{-1})	Chemical fertilizer application rate					Burning rice residue (Mg ha^{-1} yr^{-1})	Manure application rate				Manure application period
				Type	Total amount applied (kg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})				Total amount applied (Mg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})			
						N	P	K			N	P	K	
I2	Major rice	4.6	124.40	46-0-0	150	69	0	0	0	4.83	63.76	27.53	44.92	Every year
				16-16-8	113	18.08	18.08	9.04						
				16-20-0	81	12.96	16.2	0						
				0-0-60	50	0	0	30						
				Total	394	100.04	34.28	39.04						
	Second rice	3.24	-	46-0-0	113	51.98	0	0	0	0	0	0	0	
				16-16-8	100	16	16	8						
				16-20-0	81	12.96	16.2	0						
				Total	294	80.94	32.2	8						
I3	Major rice	4.92	129.92	46-0-0	138	63.48	0	0	0	4.85	64.02	27.65	45.11	
				16-16-8	163	26.08	26.08	13.04						
				16-20-0	63	10.08	12.6	0						
				0-0-60	31	0	0	18.6						
				Total	395	99.64	38.68	31.64						
I4	Major rice	3.84	104.54	46-0-0	113	51.98	0	0	0	4.43	58.48	25.25	41.20	
				15-15-15	31	4.65	4.65	4.65						
				16-20-0	69	11.04	13.8	0						
				16-16-8	138	22.08	22.08	11.04						

				Total	351	89.75	40.53	15.69						
I5	Major rice	3.93	100.13	46-0-0	138	63.48	0	0	0	4.41	58.21	25.14	41.01	
				16-16-8	131	20.96	20.96	10.48						
				16-20-0	63	10.08	12.6	0						
				0-0-60	19	0	0	11.4						
				Total	351	94.52	33.56	21.88						
I7	Major rice	3.74	57.52	46-0-0	138	63.48	0	0	0	2.79	36.83	15.90	25.95	
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	31	4.96	6.2	0						
				Total	288	87.48	25.24	9.52						
I13	Major rice	3.76	52.88	46-0-0	138	63.48	0	0	0.108	3.65	48.18	20.81	33.95	
				16-16-8	131	20.96	20.96	10.48						
				16-20-0	50	8	10	0						
				0-0-60	50	0	0	30						
				Total	369	92.44	30.96	40.48						
I1	Major rice	3.41	37.81	46-0-0	131	60.26	0	0	0.126	3.32	43.82	18.92	30.88	Every other year
				16-16-8	100	16	16	8						
				16-20-0	131	20.96	26.2	0						
				Total	362	97.22	42.2	8						
	Second rice	2.30	-	46-0-0	113	51.98	0	0	0	0	0	0	0	
				16-16-8	100	16	16	8						
				16-20-0	81	12.96	16.2	0						
				Total	294	80.94	32.2	8						
I6	Major rice	3.86	64.54	46-0-0	138	63.48	0	0	0	2.78	36.70	15.85	25.85	
				16-20-0	88	14.08	17.6	0						
				16-16-8	131	20.96	20.96	10.48						
				Total	357	98.52	38.56	10.48						
	Second rice	2.93	-	46-0-0	138	63.48	0	0	0	0	0	0	0	
				15-15-15	100	15	15	15						

				16-20-0	69	11.04	13.8	0						
				Total	307	89.52	28.8	15						
I10	Major rice	4.62	52.10	16-16-8	131	20.96	20.96	10.48	0.105	3.63	47.92	20.69	33.76	
				46-0-0	150	69	0	0						
				16-20-0	81	12.96	16.2	0						
				Total	362	102.92	37.16	10.48						
	Second rice	2.86	-	16-16-8	100	16	16	8	0	0	0	0	0	
				46-0-0	119	54.74	0	0						
				16-8-8	88	14.08	7.04	7.04						
				Total	307	84.82	23.04	15.04						
I14	Major rice	2.43	39.40	46-0-0	131	60.26	0	0	0.125	3.33	43.96	18.98	30.97	
				15-15-15	100	15	15	15						
				16-20-0	50	8	10	0						
				16-8-8	63	10.08	5.04	5.04						
				Total	344	93.34	30.04	20.04						
I15	Major rice	3.65	49.18	46-0-0	119	54.74	0	0	0.135	2.66	35.11	15.16	24.74	
				15-15-15	100	15	15	15						
				16-20-0	69	11.04	13.8	0						
				16-16-8	50	8	8	4						
				Total	338	88.78	36.8	19						
I18	Major rice	1.95	23.71	46-0-0	119	54.74	0	0	0	2.57	33.92	14.65	23.90	
				15-15-15	113	16.95	16.95	16.95						
				16-20-0	50	8	10	0						
				16-8-8	50	8	4	4						
				Total	332	87.69	30.95	20.95						
I19	Major rice	2.04	21.43	46-0-0	138	63.48	0	0	0	2.58	34.06	14.71	23.99	
				16-20-0	50	8	10	0						
				16-16-8	100	16	16	8						
				Total	288	87.48	26	8						

I20	Major rice	2.95	45.96	46-0-0	138	63.48	0	0	0.134	2.65	34.98	15.11	24.65	
				16-20-0	81	12.96	16.2	0						
				16-16-8	119	19.04	19.04	9.52						
				Total	338	95.48	35.24	9.52						
I23	Major rice	1.84	11.14	46-0-0	100	46	0	0	0.153	2.47	32.60	14.08	22.97	
				15-15-15	100	15	15	15						
				16-20-0	81	12.96	16.2	0						
				Total	281	73.96	31.2	15						
I24	Major rice	1.80	17.03	46-0-0	88	40.48	0	0	0.15	2.46	32.47	14.02	22.88	
				15-15-15	100	15	15	15						
				16-20-0	81	12.96	16.2	0						
				Total	269	68.44	31.2	15						
I8	Major rice	3.69	49.43	46-0-0	138	54.74	0	0	0	0	0	0	0	Without manure application for more than 5 years
				16-20-0	119	22.08	27.6	0						
				16-16-8	31	4.96	4.96	2.48						
				Total	288	81.78	32.56	2.48						
	Second rice	3.10	-	46-0-0	131	60.26	0	0	0	0	0	0	0	
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	81	12.96	16.2	0						
				Total	331	92.26	35.24	9.52						
I9	Major rice	3.32	33.37	46-0-0	131	60.26	0	0	0	0	0	0	0	
				16-16-8	131	20.96	20.96	10.48						
				16-20-0	31	4.96	6.2	0						
				Total	293	86.18	27.16	10.48						
I11	Major rice	1.97	36.89	46-0-0	119	54.74	0	0	0	0	0	0	0	
				15-15-15	50	7.5	7.5	7.5						
				16-20-0	113	18.08	22.6	0						
				Total	282	80.32	30.1	7.5						
I12	Major rice	2.08	34.42	46-0-0	119	54.74	0	0	0	0	0	0	0	

				15-15-15	119	17.85	17.85	17.85						
				16-20-0	50	8	10	0						
				16-8-8	50	8	4	4						
				Total	338	88.59	31.85	21.85						
I16	Major rice	1.58	10.11	16-16-8	119	19.04	19.04	9.52	0.177	0	0	0	0	
				46-0-0	131	60.26	0	0						
				Total	250	79.3	19.04	9.52						
I17	Major rice	1.50	10.57	46-0-0	150	69	0	0	0.172	0	0	0	0	
				16-16-8	100	16	16	8						
				Total	250	85	16	8						
I21	Major rice	1.56	14.66	46-0-0	163	74.98	0	0	0.166	0	0	0	0	
				16-16-8	100	16	16	8						
				Total	263	90.98	16	8						
I22	Major rice	1.65	9.12	46-0-0	150	69	0	0	0.16	0	0	0	0	
				15-15-15	113	16.95	16.95	16.95						
				Total	263	85.95	16.95	16.95						

Table A-2 Main management practices, rice yield, and SOC in rain-fed areas (n = 40)

Site No.	Rice season	Rice yield (Mg ha^{-1} yr^{-1})	SOC (Mg C ha^{-1})	Chemical fertilizer application rate					Burning rice residue (Mg ha^{-1} yr^{-1})	Manure application rate				Manure application period
				Type	Total amount applied (kg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})				Total amount applied (Mg ha^{-1} yr^{-1})	Nutrients (kg ha^{-1} yr^{-1})			
						N	P	K			N	P	K	
R14	Major rice	3.62	101.39	46-0-0	138	63.48	0.00	0.00	0	2.8	36.96	15.96	26.04	Every year
				16-16-8	100	16.00	16.00	8.00						
				16-20-0	100	16.00	20.00	0.00						
				0-0-60	63	0.00	0.00	37.80						
				Total	401	95.48	36.00	45.80						
	Second rice	2.49	-	46-0-0	100	46.00	0.00	0.00	0	0	0	0	0	
				16-16-8	100	16.00	16.00	8.00						
				16-20-0	69	11.04	13.80	0.00						
				Total	269	73.04	29.80	8.00						
R15	Major rice	3.78	114.16	46-0-0	138	63.48	0.00	0.00	0	2.8	36.96	15.96	26.04	
				16-16-8	138	22.08	22.08	11.04						
				16-20-0	119	19.04	23.80	0.00						
				Total	395	104.60	45.88	11.04						
R8	Major rice	3.52	112.04	46-0-0	163	74.98	0.00	0.00	0	2.8	36.96	15.96	26.04	
				16-8-8	100	16.00	8.00	8.00						
				16-20-0	138	22.08	27.60	0.00						
				Total	401	113.06	35.60	8.00						
R20	Major rice	3.45	69.44	46-0-0	119	54.74	0.00	0.00	0	2.6	34.32	14.82	24.18	
				16-16-8	150	24.00	24.00	12.00						

				16-20-0	19	3.04	3.80	0.00						
				Total	288	81.78	27.80	12.00						
R24	Major rice	3.35	63.96	46-0-0	131	60.26	0.00	0.00	0	2.6	34.32	14.82	24.18	
				15-15-15	63	9.45	9.45	9.45						
				16-20-0	100	16.00	20.00	0.00						
				Total	294	85.71	29.45	9.45						
R17	Major rice	3.28	77.87	46-0-0	131	60.26	0.00	0.00	0	2.5	33	14.25	23.25	
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	119	19.04	23.80	0.00						
				Total	369	98.34	42.84	9.52						
R19	Major rice	3.37	59.29	46-0-0	131	60.26	0.00	0.00	0	2.62	34.584	14.934	24.366	Every other year
				15-15-15	100	15.00	15.00	15.00						
				16-20-0	50	8.00	10.00	0.00						
				Total	281	83.26	25.00	15.00						
R18	Major rice	3.19	50.57	46-0-0	138	63.48	0.00	0.00	0	2.55	33.66	14.535	23.715	
				16-16-8	138	22.08	22.08	11.04						
				0-0-60	100	0.00	0.00	60.00						
				Total	376	85.56	22.08	71.04						
R12	Major rice	3.20	53.78	46-0-0	138	63.48	0.00	0.00	0	2.5	33	14.25	23.25	
				16-8-8	100	16.00	8.00	8.00						
				16-20-0	150	24.00	30.00	0.00						
				Total	388	103.48	38.00	8.00						
R13	Major rice	3.15	53.13	46-0-0	131	60.26	0.00	0.00	0	2.5	33	14.25	23.25	
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	119	19.04	23.80	0.00						
				Total	369	98.34	42.84	9.52						
R1	Major rice	2.53	28.28	46-0-0	119	54.74	0.00	0.00	0.206	2.4	31.68	13.68	22.32	

				16-20-0	150	24.00	30.00	0.00						
				16-16-8	119	19.04	19.04	9.52						
				Total	388	97.78	49.04	9.52						
R2	Major rice	2.49	22.54	46-0-0	100	46.00	0.00	0.00	0.211	2.4	31.68	13.68	22.32	
				16-16-8	100	16.00	16.00	8.00						
				16-20-0	69	11.04	13.80	0.00						
				Total	269	73.04	29.80	8.00						
R3	Major rice	2.48	18.75	46-0-0	131	60.26	0.00	0.00	0.212	2.3	30.36	13.11	21.39	
				15-15-15	81	12.15	12.15	12.15						
				16-20-0	50	8.00	10.00	0.00						
				Total	262	80.41	22.15	12.15						
R28	Major rice	2.22	21.83	46-0-0	119	54.74	0.00	0.00	0.216	2.13	28.116	12.141	19.809	
				16-16-8	100	16.00	16.00	8.00						
				0-0-60	50	0.00	0.00	30.00						
				Total	269	70.74	16.00	38.00						
R27	Major rice	2.14	25.46	46-0-0	100	46.00	0.00	0.00	0.22	2.13	28.116	12.141	19.809	
				16-20-0	50	8.00	10.00	0.00						
				16-16-8	50	8.00	8.00	4.00						
				Total	200	62.00	18.00	4.00						
R26	Major rice	2.11	18.93	46-0-0	88	40.48	0.00	0.00	0.222	2.16	28.512	12.312	20.088	
				15-15-15	50	7.50	7.50	7.50						
				16-16-8	50	8.00	8.00	4.00						
				Total	188	55.98	15.50	11.50						
R31	Major rice	2.06	22.55	46-0-0	100	46.00	0.00	0.00	0.228	1.7	22.44	9.69	15.81	
				16-20-0	38	6.08	7.60	0.00						
				16-16-8	31	4.96	4.96	2.48						
				Total	169	57.04	12.56	2.48						

R34	Major rice	2.05	19.30	46-0-0	100	46.00	0.00	0.00	0.227	1.6	21.12	9.12	14.88	
				15-15-15	38	5.70	5.70	5.70						
				16-20-0	31	4.96	6.20	0.00						
				Total	169	56.66	11.90	5.70						
R23	Major rice	2.04	18.55	46-0-0	88	40.48	0.00	0.00	0.253	1.3	17.16	7.41	12.09	
				15-15-15	50	7.50	7.50	7.50						
				16-20-0	31	4.96	6.20	0.00						
				Total	169	52.94	13.70	7.50						
R40	Major rice	2.03	13.23	46-0-0	100	46.00	0.00	0.00	0.257	1.5	19.8	8.55	13.95	
				15-15-15	50	7.50	7.50	7.50						
				16-20-0	19	3.04	3.80	0.00						
				Total	169	56.54	11.30	7.50						
R32	Major rice	2.60	30.10	46-0-0	119	54.74	0.00	0.00	0	0	0	0	0	Without manure application for more than 5 years
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	81	12.96	16.20	0.00						
				0-0-60	50	0.00	0.00	30.00						
				Total	369	86.74	35.24	39.52						
R33	Major rice	2.53	29.76	46-0-0	138	63.48	0.00	0.00	0.321	0	0	0	0	
				15-15-15	31	4.65	4.65	4.65						
				16-20-0	63	10.08	12.60	0.00						
				16-16-8	119	19.04	19.04	9.52						
				Total	351	97.25	36.29	14.17						
R39	Major rice	2.48	28.23	46-0-0	119	54.74	0.00	0.00	0.324	0	0	0	0	
				16-16-8	119	19.04	19.04	9.52						
				16-20-0	88	14.08	17.60	0.00						
				0-0-60	19	0.00	0.00	11.40						
				Total	345	87.86	36.64	20.92						

R4	Major rice	2.22	26.24	46-0-0	100	46.00	0.00	0.00	0	0	0	0	0	
				16-16-8	100	16.00	16.00	8.00						
				16-20-0	63	10.08	12.60	0.00						
				Total	263	72.08	28.60	8.00						
R5	Major rice	2.17	20.03	46-0-0	150	69.00	0.00	0.00	0	0	0	0	0	
				16-20-0	50	8.00	10.00	0.00						
				16-16-8	63	10.08	10.08	5.04						
				Total	263	87.08	20.08	5.04						
R7	Major rice	2.14	21.21	46-0-0	119	54.74	0.00	0.00	0	0	0	0	0	
				16-16-8	38	6.08	6.08	3.04						
				16-20-0	100	16.00	20.00	0.00						
				Total	257	76.82	26.08	3.04						
R9	Major rice	2.11	32.96	46-0-0	100	46.00	0.00	0.00	0	0	0	0	0	
				16-16-8	69	11.04	11.04	5.52						
				16-20-0	81	12.96	16.20	0.00						
				Total	250	70.00	27.24	5.52						
R38	Major rice	2.08	13.62	46-0-0	119	54.74	0.00	0.00	0	0	0	0	0	
				15-15-15	31	4.65	4.65	4.65						
				16-16-8	38	6.08	6.08	3.04						
				Total	188	65.47	10.73	7.69						
R37	Major rice	2.00	17.03	46-0-0	100	46.00	0.00	0.00	0	0	0	0	0	
				16-20-0	38	6.08	7.60	0.00						
				16-16-8	38	6.08	6.08	3.04						
				Total	176	58.16	13.68	3.04						
R36	Major rice	2.00	8.86	46-0-0	119	54.74	0.00	0.00	0.348	0	0	0	0	
				16-20-0	88	14.08	17.60	0.00						
				16-8-8	19	3.04	1.52	1.52						

				Total	226	71.86	19.12	1.52						
R35	Major rice	1.98	8.75	46-0-0	100	46.00	0.00	0.00	0.341	0	0	0	0	
				15-15-15	69	10.35	10.35	10.35						
				16-20-0	69	11.04	13.80	0.00						
				Total	238	67.39	24.15	10.35						
R25	Major rice	1.96	14.09	46-0-0	138	63.48	0.00	0.00	0.264	0	0	0	0	
				16-16-8	113	18.08	18.08	9.04						
				16-20-0	100	16.00	20.00	0.00						
				Total	351	97.56	38.08	9.04						
R30	Major rice	1.90	21.49	46-0-0	119	54.74	0.00	0.00	0	0	0	0	0	
				15-15-15	31	4.65	4.65	4.65						
				16-16-8	31	4.96	4.96	2.48						
				Total	181	64.35	9.61	7.13						
R10	Major rice	1.80	9.87	46-0-0	100	46.00	0.00	0.00	0	0	0	0	0	
				15-15-15	50	7.50	7.50	7.50						
				16-20-0	31	4.96	6.20	0.00						
				Total	181	58.46	13.70	7.50						
R16	Major rice	1.71	6.61	46-0-0	138	63.48	0.00	0.00	0.343	0	0	0	0	
				16-16-8	100	16.00	16.00	8.00						
				Total	238	79.48	16.00	8.00						
R6	Major rice	1.66	9.49	46-0-0	138	63.48	0.00	0.00	0.345	0	0	0	0	
				15-15-15	100	15.00	15.00	15.00						
				Total	238	78.48	15.00	15.00						
R11	Major rice	1.53	7.84	46-0-0	113	51.98	0.00	0.00	0	0	0	0	0	
				16-16-8	81	12.96	12.96	6.48						
				Total	194	64.94	12.96	6.48						
R29	Major rice	1.42	4.40	16-20-0	63	10.08	12.60	0.00	0.362	0	0	0	0	

				16-16-8	100	16.00	16.00	8.00						
				Total	163	26.08	28.60	8.00						
R22	Major rice	1.34	3.76	46-0-0	150	69.00	0.00	0.00	0.362	0	0	0	0	
				Total	150	69.00	0.00	0.00						
R21	Major rice	1.29	3.78	46-0-0	150	69.00	0.00	0.00	0.372	0	0	0	0	
				Total	150	69.00	0.00	0.00						

Table A-3 Simulated rice yields and SOC of each site under the A2 and B2 scenarios and the baseline in irrigated areas

Site No.	Rice yield (Mg ha^{-1} yr^{-1})					SOC (Mg C ha^{-1})				
	Baseline	**2030A2**	**2060A2**	**2030B2**	**2060B2**	**Baseline**	**2030A2**	**2060A2**	**2030B2**	**2060B2**
I1	3.4	4.0	4.7	2.9	3.5	49.6	31.4	26.0	33.9	32.4
I2	4.6	4.3	6.0	5.0	4.1	114.8	106.2	109.4	107.0	107.9
I3	4.9	6.0	6.8	5.2	5.2	118.4	110.6	114.7	112.7	113.3
I4	3.8	5.4	6.2	4.8	4.9	98.4	99.8	101.6	101.6	102.2
I5	3.9	5.0	6.6	3.5	4.4	96.4	96.9	99.0	98.5	99.5
I6	3.9	4.4	6.1	4.3	4.8	57.9	64.7	65.9	67.3	67.9
I7	3.7	6.3	6.5	4.0	4.9	54.9	52.4	54.3	53.6	54.0
I8	3.7	4.9	5.6	3.9	4.3	42.8	32.7	27.5	32.8	34.4
I9	3.3	4.5	5.9	4.1	5.0	30.8	24.2	17.6	26.6	25.3
I10	4.6	4.4	6.1	4.3	4.8	68.1	48.0	45.8	48.8	47.4
I11	2.0	3.5	4.1	2.3	2.6	31.2	23.2	19.8	22.7	22.9
I12	2.1	4.0	4.4	3.1	3.1	31.8	19.2	11.7	23.7	21.6
I13	3.8	5.2	5.5	3.8	4.4	42.2	30.6	29.2	31.9	30.9
I14	2.4	3.7	4.8	3.4	3.1	26.2	22.1	18.0	23.7	23.1
I15	3.7	4.0	4.2	2.8	3.5	36.1	32.0	28.8	33.3	30.9
I16	1.6	3.7	3.0	1.9	2.7	11.8	2.2	0.0	3.6	1.5
I17	1.5	3.5	3.9	2.3	2.7	12.0	2.3	0.0	3.8	3.4
I18	2.0	3.6	4.4	2.3	2.9	18.1	14.4	15.1	15.1	15.7
I19	2.0	3.6	4.3	2.7	3.2	23.8	20.4	21.6	20.9	20.9
I20	3.0	3.9	4.6	3.3	3.7	35.9	24.2	17.6	26.6	24.2
I21	1.6	3.1	3.8	2.0	2.5	11.9	6.1	4.6	7.5	6.6

I22	1.7	3.2	2.8	1.6	2.1	8.2	2.5	1.0	3.7	2.9
I23	1.8	3.2	3.5	1.8	2.8	8.5	2.7	1.2	3.9	2.2
I24	1.8	3.6	4.3	2.5	2.8	15.0	7.8	5.1	9.2	8.9

Table A-4 Simulated rice yields and SOC of each site under the A2 and B2 scenarios and the baseline in rain-fed areas

Site No.	Rice yield (Mg ha^{-1} yr^{-1})					SOC (Mg C ha^{-1})				
	Baseline	2030A2	2060A2	2030B2	2060B2	Baseline	2030A2	2060A2	2030B2	2060B2
R1	2.5	4.6	5.3	3.2	3.8	28.9	19.8	15.3	21.7	20.4
R2	2.5	4.5	4.9	3.9	4.4	23.0	16.3	14.0	17.7	16.6
R3	2.5	4.4	5.1	3.9	4.4	24.8	15.4	10.7	18.7	17.3
R4	2.2	3.9	4.6	2.5	3.1	33.0	20.3	12.6	25.6	23.1
R5	2.2	3.2	5.2	2.8	3.3	25.4	11.7	3.2	19.1	16.7
R6	1.7	4.2	4.5	2.3	2.8	12.8	5.3	2.0	8.3	7.6
R7	2.1	4.6	4.2	3.4	3.9	19.1	8.6	2.9	12.9	10.5
R8	3.5	4.4	6.2	3.9	4.4	108.6	95.6	87.7	101.4	98.0
R9	2.1	4.3	5.0	3.4	4.0	42.8	33.4	28.7	36.6	35.2
R10	1.8	2.7	3.9	2.4	2.9	12.9	6.8	5.0	8.2	5.9
R11	1.5	3.0	4.6	2.2	2.8	10.7	5.8	4.2	7.1	4.6
R12	3.2	4.4	5.2	3.2	3.7	65.1	51.5	50.7	52.9	56.5
R13	3.2	4.4	5.4	3.6	4.2	50.0	42.4	39.2	43.5	42.8
R14	3.6	4.8	6.2	4.0	4.6	114.5	95.9	87.6	98.2	101.8
R15	3.8	6.1	6.0	5.1	5.6	81.9	68.2	59.7	72.5	70.1
R16	1.7	4.5	4.5	3.5	4.1	10.2	2.7	0.5	4.0	2.6
R17	3.3	4.6	4.9	3.4	4.0	76.2	63.8	56.5	65.0	68.6

R18	3.2	3.8	4.6	3.3	3.8	57.9	48.7	44.3	52.7	51.3
R19	3.4	4.6	5.8	4.2	4.8	79.9	56.4	49.9	60.7	58.3
R20	3.5	6.8	6.8	5.2	5.7	58.6	50.5	46.9	51.6	50.9
R21	1.3	2.2	2.5	2.0	2.5	5.6	1.9	1.3	2.4	2.1
R22	1.3	3.5	4.2	2.2	2.7	5.6	1.5	0.6	1.9	2.3
R23	2.0	4.7	4.5	3.6	4.2	28.2	14.7	9.0	18.0	15.6
R24	3.4	5.5	5.5	4.4	4.9	77.9	59.3	52.6	59.6	61.2
R25	2.0	3.2	4.3	4.2	4.8	14.6	8.1	3.4	9.4	13.0
R26	2.1	2.6	2.9	2.2	2.7	27.6	13.5	7.3	17.2	14.8
R27	2.1	4.4	4.9	3.3	3.8	32.1	19.0	11.8	21.6	20.2
R28	2.2	3.8	4.0	2.5	3.0	30.4	15.9	10.3	17.2	18.8
R29	1.4	3.9	4.1	2.1	2.7	7.0	2.3	1.7	2.5	2.2
R30	1.9	3.1	4.1	2.6	3.1	19.3	13.9	7.4	17.1	18.6
R31	2.1	3.6	3.8	2.5	3.1	22.2	13.7	11.3	16.9	14.4
R32	2.6	3.5	4.7	2.8	3.4	39.2	26.7	21.9	28.1	27.7
R33	2.5	4.7	5.2	4.9	5.4	26.2	21.0	17.5	21.6	21.1
R34	2.1	4.3	4.8	2.8	3.3	18.2	14.1	11.5	15.6	14.9
R35	2.0	3.2	4.5	2.9	3.4	9.1	4.9	2.2	6.5	6.0
R36	2.0	3.2	4.2	2.6	3.2	12.2	4.2	2.4	5.4	5.2
R37	2.0	4.6	5.4	3.7	4.2	14.5	9.3	5.7	10.7	12.5
R38	2.1	5.7	5.1	3.8	4.3	21.8	8.7	4.3	10.3	8.9
R39	2.5	3.7	4.4	3.2	3.8	27.0	21.2	17.0	24.6	23.7
R40	2.0	3.1	3.9	2.5	3.1	11.9	10.7	8.9	12.0	11.0