

**AGRICULTURAL LAND MANAGEMENT IN RAIN-FED RICE FIELD  
USING ENERGY CROP ROTATION**

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IN ENVIRONMENTAL TECHNOLOGY**

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Agricultural Land Management in Rain-Fed Rice Field using Energy Crop Rotation

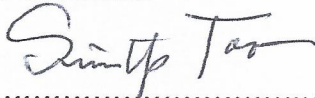
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for the Degree of Doctor of Philosophy  
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The Joint Graduate School of Energy and Environment  
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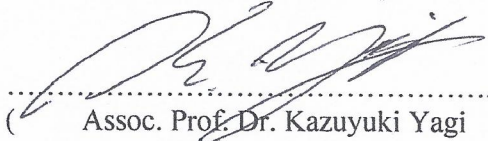
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### ABSTRACT

This study aims to find a suitable crop rotation system in rice fields for mitigating greenhouse gas (GHG) emissions and improving soil carbon sequestration in order to enhance the utilization of fallow period in rain-fed rice fields and gain more benefits from agricultural land. Field experiments were carried out for two years and six months in which a crop rotation was made in the dry season and rain-fed rice was grown in the wet season. Four different dry season cases were studied: fallow (RF), irrigated rice (RR), corn (RC), and sweet sorghum (RS). Emissions of methane (CH<sub>4</sub>), carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) were estimated using the closed-chamber method. Soil carbon budget (SCB), soil organic carbon (SOC) stock and crop yields were also measured. This study found that the RC and RS reduced the CH<sub>4</sub> emission by 78-84%, and reduced the total global warming potential (CH<sub>4</sub> and N<sub>2</sub>O) by 59-73% compared with continuous rice (RR). The SCB in rotation with corn showed the highest gain in the second year. The SOC stocks were maintained by the RR, RC and RS treatments, but significantly decreased by the RF treatment in the second year. The rice grain yields of RC and RS were stable in the both years, while RF fell slightly by 11%, and RR significantly reduced by 39% from the first year. The DNDC model simulation of CH<sub>4</sub> emissions and SOC storage from energy crop rotation in rain-fed rice field was sufficiently good for practical use of the model in both short and long term prediction. These results indicated that RC and RS not only reduced GHG emissions but also improved SOC stock and crop yields. Although RF able to reduce GHG emission by 66% compared with RR, but there lose in soil carbon sequestration and agricultural land utilization.

**Keywords:** Rain-fed rice, Crop rotation, Greenhouse gas, Soil carbon sequestration, Rice yield, DNDC model

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# CHAPTER 1

## INTRODUCTION

### 1.1 Rationale / Problem Statement

Rain-fed agriculture is a major source of the food production in many countries around the world (Suhas P. Wani *et al.*, 2009). Approximately 165 million ha were global rice productions, of which 52 million ha devoted to rain-fed lowlands rice. Rice is produced and consumed in Asia covers about 147 million ha or almost 90% of the world rice harvested area (FAOSTAT, 2013; GRiSP, 2013). Rain-fed lowland rice in Southeast Asia covers about 20 million ha or about 38% of the global rain-fed rice area (Mutert and Fairhurst, 2002; FAOSTAT, 2013; GRiSP, 2013). In Thailand, rice remains an important economic crop. Its cultivation area covers about 11 million ha or approximately 47% of the country's arable land, and 60% of this rice cultivation is rain-fed (OAE, 2012). The main constraints of the rain-fed rice production are rainfall variability, drought, submergence and poor soil fertility (GRiSP, 2013). Many rain-fed rice areas in Thailand have low soil fertility (Jongdee *et al.*, 1997) and over 200,000 ha have been abandoned (LDD, 2010). In general, rice cultivation in rain-fed area is about four months in the rainy season, and then being left as the fallow period approximately eight months in the dry season (OAE, 2008, 2012). Due to its poor management during fallow period, loss in soil fertility and nutrition occurred. It is therefore inappropriate to grow the second rice. Hence, farmers that have rain-fed rice field often lost their opportunity to double their cultivation in one year, which is a general practice in irrigated rice field.

Crop rotation in rice field can improve utilization of agricultural land, however different crop systems and managements have shown different effects on GHG emissions (Adhya *et al.*, 2000; Zheng *et al.*, 2000; Nishimura *et al.*, 2008; Datta *et al.*, 2011; Zhou *et al.*, 2014). Rice in rotation with upland crop is unique from other wetland or upland soils because they are associated with frequent cycling between wetting and drying under anaerobic and aerobic conditions (Zhou *et al.*, 2014). During rice growing season, methane (CH<sub>4</sub>) is produced and emitted to the atmosphere mainly through the rice plant. While, during upland crop, CH<sub>4</sub> is oxidized into CO<sub>2</sub> (Le Mer and Roger, 2001). Agricultural soil management activities by chemical fertilizer or manure application are the main source of nitrous oxide (N<sub>2</sub>O) emission (Lal, 2007; Nishimura *et al.*, 2008).

FAOSTAT (2013) and IPCC (2014) reported that agricultural sector is the largest contributor to global anthropogenic non-CO<sub>2</sub> greenhouse gases (GHGs). The annual total non-CO<sub>2</sub> GHG emissions from agriculture in 2010 were 5.2-5.8 Gt CO<sub>2</sub>eq year<sup>-1</sup>, accounting for 10-12% of global anthropogenic emissions. Rice cultivation alone emitted 493-723 Mt CO<sub>2</sub>eq year<sup>-1</sup> (FAOSTAT, 2013; IPCC, 2014). Thailand is an agricultural country. Total area of Thailand is 513,100 square kilometers that is covering agriculture area approximately 208,500 square kilometers (OAE, 2008). Agricultural emissions make up more than 22% (51.88 Mt CO<sub>2</sub>eq) of annual GHG emissions. These emissions are disaggregated into 57.7% from rice cultivation, 15.9% from enteric fermentation, 14.6% from agricultural soil, 9.8% from manure management and 1.9% from field burning of agricultural residues (ONEP, 2010). Due to this relatively large contribution to global GHG emissions, improved field management of agricultural systems may reduce their global warming potential by mitigating GHG emissions, increasing soil carbon content, and supplanting fossil feed stocks through the production of cellulosic feed stocks for biofuels (CAST, 2011).

Although the rice cultivation increased GHG emissions, many references indicated that the use of suitable cropping systems and plant residue management methods can improve soil organic carbon (SOC) sequestration. These can reduce carbon loss to the atmosphere, lead to increasing soil fertility and improving crop productivity (Li and Feng, 2002; Qiu *et al.*, 2005; Tang *et al.*, 2006; Dawson and Smith, 2007; Al-Kaisi, 2008; Nishimura *et al.*, 2008; Kukal *et al.*, 2009; Singh *et al.*, 2009; Ali *et al.*, 2012). The rotation of upland crops in rice field has affected the nutrient imbalance in the plant and soil (Deog-Bae *et al.*, 2005). During rice season, number and activity of anaerobic microbe are increasing, which not only leads to the slower decomposition of organic matter and contributes to soil organic matter (SOM) accumulation but also promotes the CH<sub>4</sub> gas that is toxic substance produced for rice plant (Ponnamperuma, 1972; Zhou *et al.*, 2014). During upland crop season, the biological N fixation is reduced and SOM mineralization is facilitated, therefore accelerating SOM loss (Witt *et al.*, 2000; Zhou *et al.*, 2014).

In Thailand, crop rotation in fallow period after the rain-fed rice is not appropriate due to soil quality and limitation of water. These fallow period areas cover 7 million ha, which is about 55% of the rice cultivation area (OAE, 2012). The second rice cultivation in these fallow areas can increase rice field over 50% (average yield is 2.8 ton ha<sup>-1</sup>) (OAE, 2012; GRiSP, 2013). However, increasing of rice cultivation period will also induce GHG emissions during rice growing season (Adhya *et al.*, 2000). The studies of impact of crop

rotation in the rice field in term of GHG emissions and SOC storage changes as the indicator of soil fertility are very few in the tropical area. Moreover, very few evidence has been studied in Thailand. Introducing of crop rotation in the rain-fed rice field help increasing utilization of poor land during fallow period.

Several agricultural management practices are known to be an important factor for GHG emissions. There are highly variable so it is difficult to integrate emissions over space and time (Smith *et al.*, 2010). Also due to the crop management practices are complex and varies with soil conditions, the field monitoring of SOC stock in continuous changes were difficult to detect in the short period (López Garrido *et al.*, 2009). In order to long-term monitoring, it is then important to use a tool for estimate and predict GHG emissions and SOC stock change from agricultural system. Therefore, the computer simulation model has been used for monitoring. The DNDC (Denitrification-Decomposition) model is a complex process based model of carbon (C) and nitrogen (N) biogeochemistry in agricultural ecosystems (Li, 2000). It was developed for predicting GHG fluxes (CH<sub>4</sub> and N<sub>2</sub>O) and SOC storage in various croplands (Li *et al.*, 1994; Li, 2000). This model was suitable for estimating the pattern of GHG emissions throughout the growing period (Li *et al.*, 2005; Babu *et al.*, 2006; Abdalla *et al.*, 2009). Simulation of soil carbon by using DNDC model has been reported by Oiu *et al.* (2005), Shirato (2005) and Wang *et al.* (2008). So, the DNDC model was useful for estimating the effect of agricultural practices on GHG emissions and SOC changes in both short-term and long-term. Accordingly, the rotation of rice and upland crops could be achievable.

Nowadays, the increasing in bio-energy tends to be greater. There is considerable interest in the short period crop rotation with fast growing crops for bio-energy production. Corn and sweet sorghum have the potential to use as feedstock for bio-ethanol production (Ban *et al.*, 2008; Holou, 2010; Wu *et al.*, 2010). These crops are also short growing period crops (about four months), low water demand, and drought resistance. Therefore, this study introduced corn and sweet sorghum as the rotation crop in the rain-fed rice field. These rotations are not only reclaim the double cropping but also help farmers to gain more benefit from their annual activities include possible higher income. These practices can be identify as sustainable agriculture and reduce poverty which is the important pillar of sustainable development goals.

Moreover, the effects of their crop rotations in rice field on GHG emissions, soil carbon dynamics and crop production have not yet been clearly revealed. Therefore, this

study aim to verify the effects of crop rotations on GHG emissions, SOC sequestrations, and rice yields by using corn, sweet sorghum and irrigated rice rotation in order to introduce alternative cultivation practices in fallow period of rain-fed rice field with crop rotations for the most utilization of the rain-fed area in Thailand. This study also use the site mode of DNDC model (version 93) in order to estimate and predict the variations of GHG emissions and SOC stocks in short-term and long-term under the different crop rotation systems.

## 1.2 Objectives

The objectives of this study are;

1.2.1 To study and quantify the GHG emissions, SCB and SOC stock in rain-fed rice field managed by energy crop rotations

1.2.2 To simulate short-term and long-term variations of GHG emissions and SOC stocks under the different crop rotation systems by site mode of DNDC model.

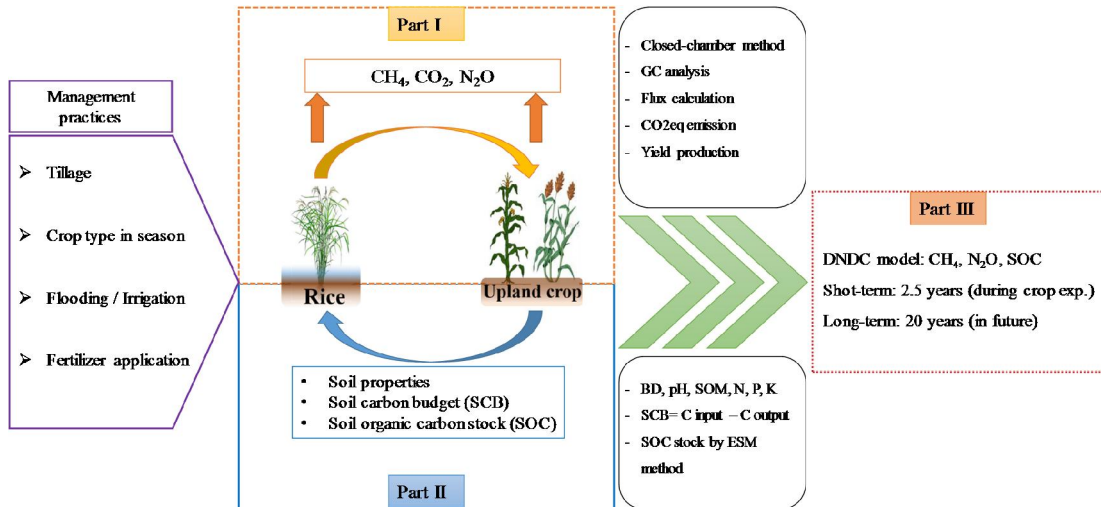
## 1.3 Scope of Research Work

This research was based on the optimization of rain-fed rice areas managed by energy crop rotations for reducing GHG emissions and increasing soil carbon sequestration in both short and long-term periods. The field experiment was carried out at King Mongkut's University of Technology Thonburi, Ratchaburi campus in Sub-district Rang Bua, Chombung District, Ratchaburi Province, Thailand. This experimental site was the abandoned rice field (fallow land condition) 10 years before the experiments began in 2010. The irrigated and rain-fed rice (*Oryza sativa*) were used Prathumthani 1 of rice variety for cultivation. Suwan 5 of corn (maize) (*Disambiguation*) variety and Khonkean 40 of sweet sorghum (*Sorghum bicolor*) variety were cultivated after rain-fed rice season.

The study of crop rotation on GHG emissions and soil carbon sequestration were investigated in four treatments:

- 1) fallow land in dry season and rain-fed rice in wet season (RF),
- 2) irrigated rice in dry season and rain-fed rice in wet season (RR),
- 3) irrigated corn in dry season and rain-fed rice in wet season (RC), and
- 4) irrigated sweet sorghum in dry season and rain-fed rice in wet season (RS).

The experiment was conducted from 2010 to 2012. This study is divided into three parts (Figure 1.1).



**Figure 1.1** Scope of research work in three parts

### Part I:

Rice and upland crop cultivations are significant sources of atmospheric GHG emissions, so Part I studies and quantifies the GHG emissions and crop yields by energy crop rotation in rain-fed rice field. The studies of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emission from rice field and energy crop were conducted at a crop field using the closed-chamber method and analyzed by gas chromatography (GC) with a flame ionization detector (FID) for CO<sub>2</sub> and CH<sub>4</sub>, Electron capture detector (ECD) for N<sub>2</sub>O. Fluxes and GHG in CO<sub>2</sub> equivalent were calculated. Crop biomass and yield production were also measured.

### Part II:

The effects of different crop rotation management practices on soil properties and soil carbon dynamics are discussed in Part II. This part studies and quantifies the soil physical and chemical properties, SCB, and SOC stock in a rain-fed rice field managed by energy crop rotation. Soil samples were collected after crop harvest and taken to analyze physical and chemical properties in the laboratory. The SCBs were estimated by integrating the amounts of net carbon supplied into the soil and removed from the soil. The SOC stocks were estimated by the equivalent soil mass method (ESM).

**Part III:**

DNDC model is useful for predicting GHG emissions and SOC stock changes due to agricultural practices in short and long periods. Thus, Part III studies and implements the process-based model (DNDC model, version 9.3) in site mode for short-term and long-term changes in GHG emissions (CH<sub>4</sub> and N<sub>2</sub>O) and SOC stocks under different crop rotation systems. This model required data of daily climate, soil and crop management. The climate data from Thai Meteorological Department (Ratchaburi station) used for spin up time simulation in period of abandoned rice field (2000-2009) and crop cultivation period (2010-2011). The future simulation (2012-2030) was conducted from the PRECIS Climate model ECAM4 SRES B2.

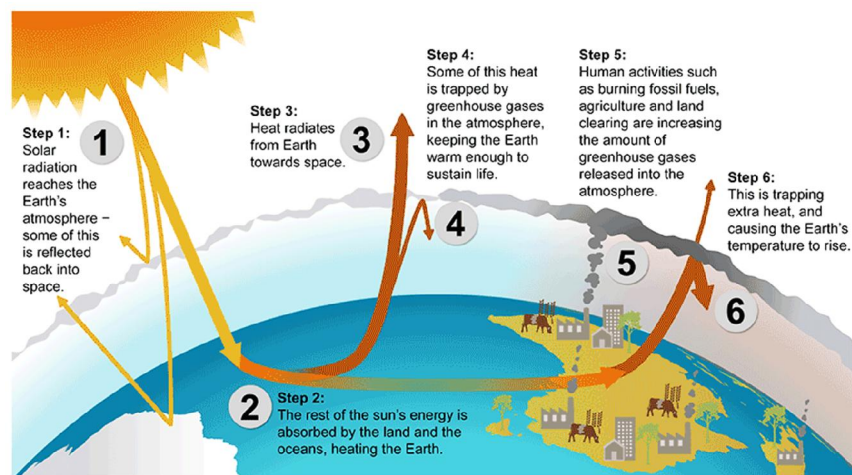
## CHAPTER 2

### THEORIES AND LITERATURE REVIEWS

This chapter presents the definition and previous studies relating to greenhouse effects and greenhouse gases (GHG), their emissions from agricultural management, agricultural situation in Thailand, soil carbon in agricultural land, energy crops for biofuel production, and effect of crop rotations. In addition, DNDC model and its application in agriculture was presented in this chapter.

#### 2.1 Greenhouse effects and Greenhouse gases

The greenhouse effect is a natural process that warms the Earth's surface. When the Sun's energy reaches the Earth's atmosphere, some of it is reflected back to space and the rest is absorbed and re-radiated by greenhouse gases. The absorbed energy warms the atmosphere and the surface of the Earth. This process maintains the Earth's temperature at around 33 degrees Celsius warmer than it would otherwise be, allowing life on Earth to exist. The problem is human activities, mainly burning fossil fuels, agriculture and land clearing are increasing the greenhouse gas emissions. This is the enhanced greenhouse effect (see Figure 2.1), which is contributing to global warming (Department of the Environment-Australian Government, 2013).



**Figure 2.1** Enhanced greenhouse effect (Department of the Environment-Australian Government, 2013)

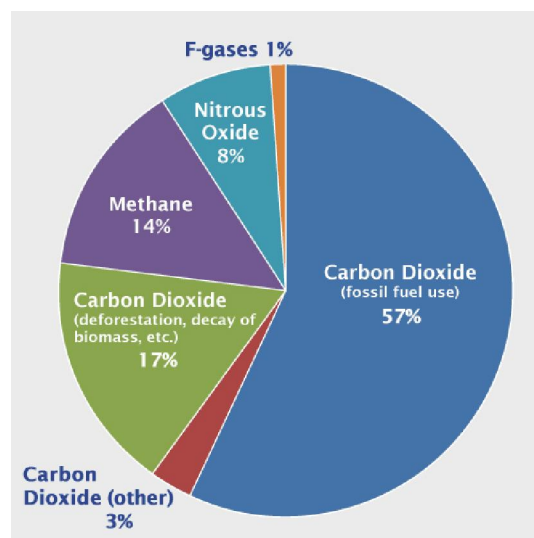
Greenhouse gases (GHG) are a group of compounds that are able to trap heat (long-wave radiation) in the atmosphere, and keeping the Earth's surface warmer. Increases in the amount of greenhouse gases in the atmosphere enhances the greenhouse effect, which is creating global warming and consequently climate change (IPCC, 2007; Allison, 2010; whatsyourimpact, 2006). The main forcing greenhouse gases are shown in Figure 2.2 (IPCC, 2007).

1) Carbon dioxide (CO<sub>2</sub>): The primary source of CO<sub>2</sub> emission through the burning of fossil fuel by 57% of total GHG emissions. The land use change is also an important source of CO<sub>2</sub>, Deforestation is emitted CO<sub>2</sub>, which accounts for 17% of total GHG emissions.

2) Methane (CH<sub>4</sub>): Livestock and agricultural activities, waste management in municipal solid waste landfill, and energy use all to contribute to 14% of total GHG emissions.

3) Nitrous oxide (N<sub>2</sub>O): Agricultural activities (fertilizer application) and industrial, as well as combustions of fossil fuels and solid waste are emitted 8% of total GHG emissions.

4) Fluorinated gases (F-gases): A group of gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>). These gases are emitted 1% of total GHG emissions from a variety of industrial process, refrigeration, and commercial and household uses.



**Figure 2.2** Global Greenhouse Gas Emissions by Gas in 2004 (IPCC, 2007)

## **2.2 Greenhouse gas emission and national greenhouse inventory from agriculture**

### **2.2.1 Greenhouse gas emissions from agricultural management**

Agricultural activities contribute directly to GHG emissions through a variety of processes: land use change, soil respiration and decomposition, livestock farming and manure, biomass burning, rice agriculture and use of fertilizer.

#### **2.2.1.1 Land use changes**

Land use change are a considerable source of CO<sub>2</sub> emissions globally, accounting for 9% of human CO<sub>2</sub> emissions and contributed 3.3 billion ton of CO<sub>2</sub> emissions in 2011 (whatsyourimpact, 2006; Le Quéré *et al.*, 2012). Land use and land use from 1850 to 2000 released an estimated 396-690 billion ton of CO<sub>2</sub> to the atmosphere, or approximately 28-40% of total anthropogenic CO<sub>2</sub> emissions (Houghton, 2010).

#### **2.2.1.2 Soil respiration and decomposition**

Soil respiration and decomposition are important natural source of CO<sub>2</sub> emissions, accounting for 28.56% of natural emissions. Soil respiration and decomposition processes release CO<sub>2</sub> as a by-product, which create about 220 billion ton of CO<sub>2</sub> emissions per annual (Denman *et al.*, 2007; U.S. DOE, 2008).

#### **2.2.1.3 Livestock farming**

Livestock farming is an important source of CH<sub>4</sub> emissions through enteric fermentation in farm animals, which is responsible for 27% of human CH<sub>4</sub> emissions (Bousquet *et al.*, 2006; whatsyourimpact, 2006). The ruminant animals such as sows, sheep and goats create large amounts of CH<sub>4</sub> during their normal digestion process. Because of microorganisms in the stomach of these animals causes enteric fermentation, which creates CH<sub>4</sub> as a by-product that is either exhaled by the animal or released via flatus (whatsyourimpact, 2006).

#### **2.2.1.4 Storage and handling of livestock manure**

One direct source of agricultural N<sub>2</sub>O emissions is the storage and handling of livestock manure. The systems of animal waste management (treatment and disposal) create conditions that are favorable for N<sub>2</sub>O producing bacteria. When the nitrogen in manure decomposes by microorganism, N<sub>2</sub>O was emitted from soil to the atmosphere through nitrification-denitrification process (whatsyourimpact, 2006).

### **2.2.1.5 Biomass burning**

Biomass burning cause a substantial amount of CH<sub>4</sub> and N<sub>2</sub>O emission. This is responsible for 11% of human CH<sub>4</sub> emission and 10% of human N<sub>2</sub>O emissions (Bousquet *et al.*, 2006). Biomass burning is the burning of material from living and dead vegetation. Incomplete burning of biomass creates CH<sub>4</sub> and N<sub>2</sub>O emissions. In these burning, some of carbon and nitrogen in the biomass and surrounding air is oxidized creating CH<sub>4</sub> and N<sub>2</sub>O emissions. The open burning is mainly used by humans to clear crop waste and crop field for agricultural or other uses.

### **2.2.1.6 Rice agriculture**

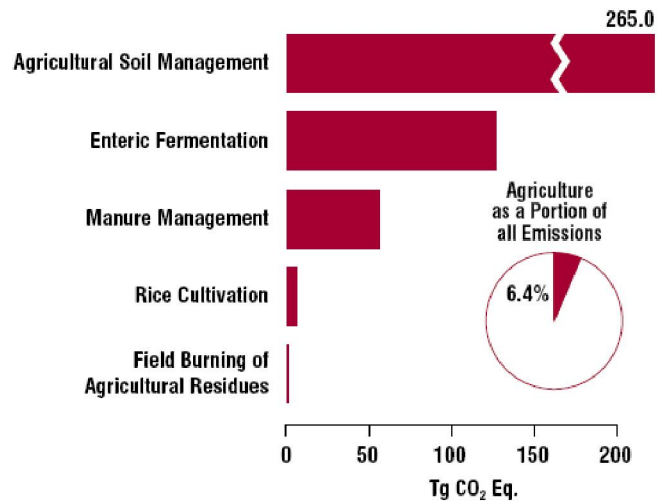
Rice agriculture is another considerable human source of CH<sub>4</sub> emissions. There are emitted from flooded soil results from CH<sub>4</sub> production. In flooded rice cultivation, CH<sub>4</sub> is produced in anaerobic soil through organic matter fermentation by methanogen bacteria, and some of CH<sub>4</sub> are consumed by methanotrophs bacteria (Le Mer and Roger, 2011). Rice agriculture creates 31 million tons of CH<sub>4</sub> annually (Bousquet *et al.*, 2006).

### **2.2.1.7 Fertilizer agricultural soils**

The use of chemical fertilizer for agriculture is a major source of N<sub>2</sub>O emissions. Fertilizers help improve plant growth by adding nitrogen to soils. The processes of nitrification and denitrification produce N<sub>2</sub>O which is then released into the atmosphere. The manure application as a fertilizer also leads to N<sub>2</sub>O emissions from agricultural soils. N<sub>2</sub>O can be created quickly when soils are warm and moist (whatsyourimpact, 2006; Denman, 2007).

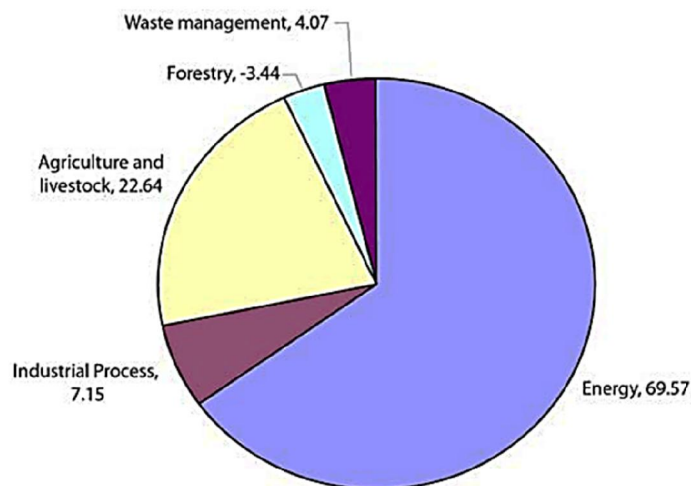
## **2.2.2 National greenhouse inventory from agriculture**

In the U.S.A, the agricultural sector provides an assessment of non-CO<sub>2</sub> emissions from the agricultural soil management, enteric fermentation in domestic livestock, manure management, rice cultivation, and field burning of agricultural residues (Figure 2.3). These are accountable for emissions of 454.1 Tg CO<sub>2</sub>eq, or 6% of total U.S. GHG emissions. CH<sub>4</sub> and N<sub>2</sub>O were the main GHGs emitted by agricultural activities. CH<sub>4</sub> emissions from enteric fermentation and manure management denote approximately 23% and 7% of total CH<sub>4</sub> emissions from anthropogenic activities, respectively. The minor sources of CH<sub>4</sub> emissions is rice cultivation and field burning of agricultural residues. Agricultural soil management activities i.e. fertilizer application and other cropping practices were the largest source of N<sub>2</sub>O emissions, accounting for 72%. A little N<sub>2</sub>O emissions come from manure management and field burning of agricultural residues (U.S. EPA, 2008).



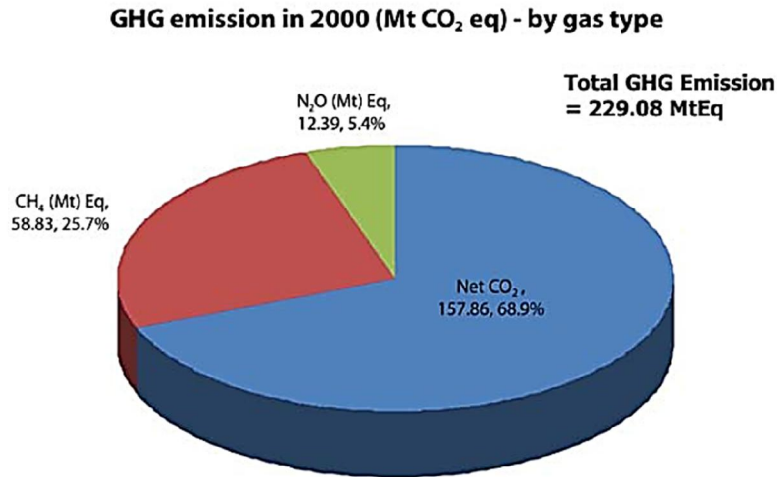
**Figure 2.3** Sources of Greenhouse Gas Emission from agricultural in 2006  
(U.S. EPA, 2008)

Thailand emitted greenhouse gases equivalent to 281 million tons of CO<sub>2</sub> in 2000. Taking into account a sink of 52 million tons, the net GHG emissions reached 229 million tons of CO<sub>2</sub> equivalent. Figure 2.4 shows GHG emissions by source. The energy sector was still the most important source, constituting about 70% of the total, followed by agriculture which recorded about 23%. The remaining 7% was shared among the industrial sector, forestry and waste management (ONEP, 2010).



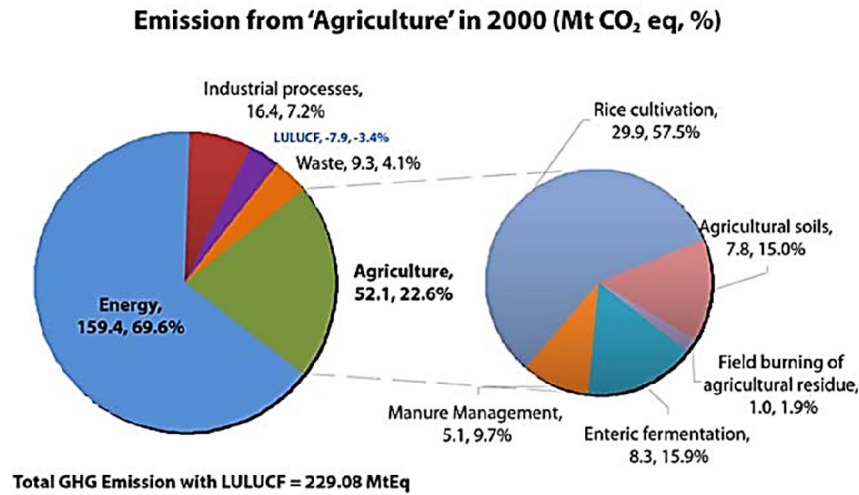
**Figure 2.4** Greenhouse gas emissions by source in CO<sub>2</sub> equivalent for 2000 (ONEP, 2010)

Comparing CO<sub>2</sub> equivalent by type of GHG emissions in Thailand in 2000, CO<sub>2</sub> constituted about 69% of the total, followed by CH<sub>4</sub> at 26%, and N<sub>2</sub>O at 5% (Figure 2.5). Hence, CO<sub>2</sub> was the most important greenhouse gas, while the energy sector was the most important source of emissions in 2000, followed by CH<sub>4</sub> emitted mainly from agriculture and livestock (ONEP, 2010).



**Figure 2.5** Greenhouse gas emissions by gas type in CO<sub>2</sub> equivalent for 2000 (ONEP, 2010)

Agriculture is the main source of CH<sub>4</sub> and N<sub>2</sub>O emissions. In 2000, agriculture produced about 70% and 83% of the total national emissions (28,000 and 40,000 tons of CH<sub>4</sub> and N<sub>2</sub>O, respectively). Rice production in flooded land emitted more than 72% of total CH<sub>4</sub> from agriculture, followed by livestock at 14%. Going by the CO<sub>2</sub> equivalent (Figure 2.6), rice cultivation was the most important source by emitting more than 57% of total emissions from agriculture. Agricultural soil and enteric fermentation from livestock contributed almost equally to agricultural emissions in CO<sub>2</sub> equivalent, while field burning was a minor source of emissions. Hence, mitigation measures should give preliminary attention to crops and livestock as well as agricultural sub-sectors (ONEP, 2010).



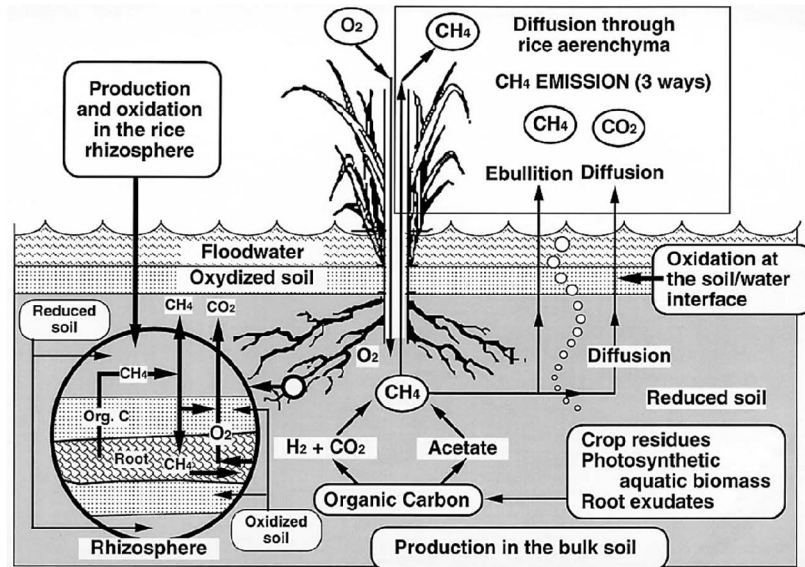
**Figure 2.6** Greenhouse gases from all sectors and agriculture by source in CO<sub>2</sub> equivalent (ONEP, 2010)

### 2.3 Methane production and oxidation in agricultural soil

Methane (CH<sub>4</sub>) emissions from agricultural soil correlated with microbial activities. CH<sub>4</sub> is produced in the anaerobic zones of submerged soils by methanogens. While, in the aerobic zones of wetland soils and in uplands soils, CH<sub>4</sub> is oxidized into CO<sub>2</sub> by methanotrophs (Le Mer and Roger, 2001).

#### 2.3.1 CH<sub>4</sub> production

In flooded soil of rice cultivation, CH<sub>4</sub> is produced in anoxic zones through fermentation by methanogenic bacteria and consumed by methanotrophs in oxidized zones (rhizosphere, lower part of culms, soil-water interface and submersion water). The most of CH<sub>4</sub> emitted through the rice aerenchyma and a lower emitted through diffusion and ebullition as bubbles escaping from the flooded soil to the atmosphere (Figure 2.7) (Le Mer and Roger, 2001).



**Figure 2.7** Methane production, consumption and transfer to the atmosphere in rice fields  
(Le Mer and Roger, 2001)

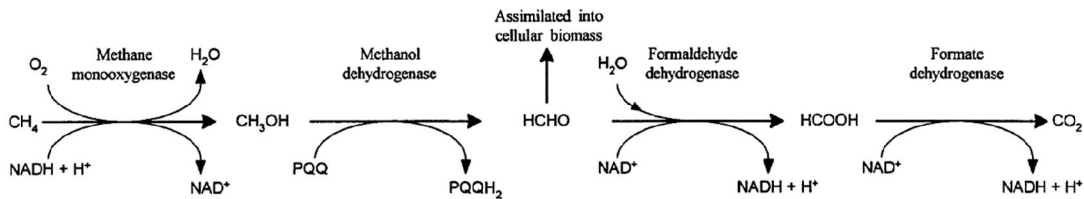
An aerenchyma of rice plant act as tubes, allowing gaseous exchanges between soil and atmosphere (Neue and Roger, 1994). Schütz *et al.*, (1989) and Jia *et al.*, (2001) were found that planted rice fields emit more CH<sub>4</sub> than wet unplanted fields because of a higher carbon (C) availability for ethanogenesis and an easier transfer to the atmosphere. Rice leaves have been filled with an aerenchyma and micropores as act pipes for CH<sub>4</sub> emission (Nouchi *et al.*, 1994). CH<sub>4</sub> emissions varied with rice varieties because of morphological differences in the aerenchyma and root porosity (Adhya *et al.*, 1994; Butterbachbahl *et al.*, 1997; Singh *et al.*, 1998). When the rice plants are little developed at the beginning of the cultivation, the main transfer mechanism is the bubble formation and vertical movement in the soil. When rice plants grow, diffusion through the aerenchyma becomes the main process, accountable for more than 90% of the CH<sub>4</sub> emitted during the reproductive phase of the rice plant (Cicerone and Shetter, 1981; Schütz *et al.*, 1989; Tyler *et al.*, 1997; Ref. in Le Mer and Roger, 2001). Jia *et al.*, (2001) was observed that CH<sub>4</sub> emission in the rice planted treatment was higher at tillering stage than at panicle initiation stage because of CH<sub>4</sub> produced was lower oxidized in the rhizosphere at rice tillering stage (36.3%) than at panicle initiation stage (54.7%).

### 2.3.2 CH<sub>4</sub> oxidation

The CH<sub>4</sub> uptake potential is only partly exploited, especially of arable soils and grassland. The several agricultural practices have contrary impacts on the activity of the CH<sub>4</sub> oxidizing bacteria (Hütsch, 2001). In the aerobic zones of wetland and upland soils, methanotrophic bacteria use CH<sub>4</sub> as sole a carbon and energy source, which can oxidize CH<sub>4</sub> to CO<sub>2</sub>.

The methanotrophic bacteria are responsible for CH<sub>4</sub> oxidation under aerobic conditions. They are unique in their ability to use CH<sub>4</sub> as only carbon and energy source. The important enzymes of aerobic methanotrophic bacteria, CH<sub>4</sub> monooxygenases (MMOs), a low substrate specificity produce in a fortuitous metabolism of a large number of compounds. Methanotrophic bacteria and chemoautotrophic ammonia oxidizers are very similar in the way they oxidize CH<sub>4</sub> and NH<sub>3</sub>, respectively (Hanson and Hanson, 1996; Hütsch, 2001). The CH<sub>4</sub> oxidation pathways in methanotrophic bacteria and of NH<sub>3</sub> oxidation in ammonia oxidizers are given in Figure. 2.8 (Hütsch, 2001).

However, the consumption of atmospheric CH<sub>4</sub> in aerobic soils are positive but amounts are very low. CH<sub>4</sub> oxidation by aerobic upland soils is infrequently higher than 0.1 mg m<sup>-2</sup> h<sup>-1</sup> (Le Mer and Roger, 2001).



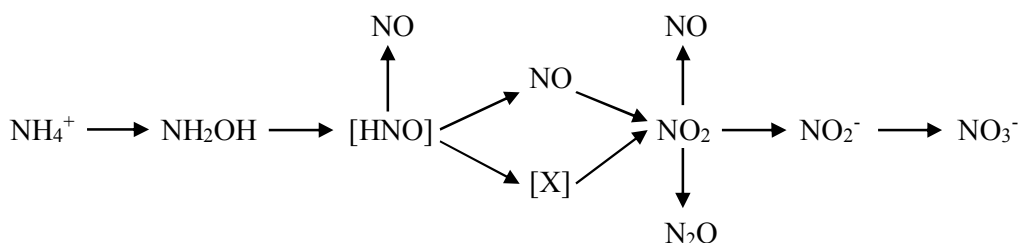
**Figure 2.8** Methane oxidation in methanotrophs (Hütsch, 2001)

### 2.4 Nitrous oxide production in agricultural soil

Nitrous oxide (N<sub>2</sub>O) is an important GHG that is predominantly emitted from soil environments. N<sub>2</sub>O is produced in the soil via nitrification and denitrification processes (Pathak, 1999).

### 2.4.1 Nitrification

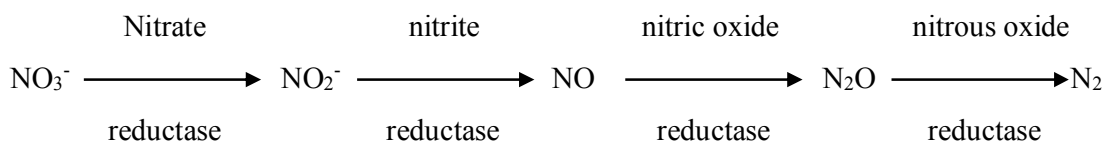
The nitrification process also contributes to  $N_2O$  emissions by oxidation of ammonium ( $NH_4^+$ ) or hydroxylamine ( $NH_2OH$ ) to nitrate ( $NO_3^-$ ), due to the addition of ammonium fertilizer or ammonia forming fertilizer to the soil.  $N_2O$  is formed during ammonia ( $NH_3$ ) oxidation through chemical decomposition of intermediates between  $NH_4^+$  and nitrite ( $NO_2^-$ ). The pathway of  $N_2O$  production during nitrification can be depicted as Figure 2.9.



**Figure 2.9** Transformation of nitrification pathway (Pathak, 1999)

### 2.4.2 Denitrification

Denitrification process occurs when  $NO_3^-$  is present in anaerobic microsites developed wherever microbial demand for oxygen ( $O_2$ ) exceeds diffusion-mediated supply. This process might well occur where  $O_2$  diffusion is impeded by water. The process of denitrification in soils also consumes  $N_2O$  through the reduction of  $N_2O$  to nitrogen ( $N_2$ ). Therefore, this bacterial process could serve either as a source or as a sink of  $N_2O$ . The simplest scheme of denitrification can be seen in Figure 2.10.



**Figure 2.10** Transformation of denitrification pathway (Pathak, 1999)

In facultative-anaerobic condition, denitrification is the stepwise reduction of  $NO_3^-$  to  $N_2$ . In contrast to nitrification,  $N_2O$  is a regular intermediate of denitrification which can be released in high quantities in low-oxygen environment with sufficient  $NO_3^-$  and

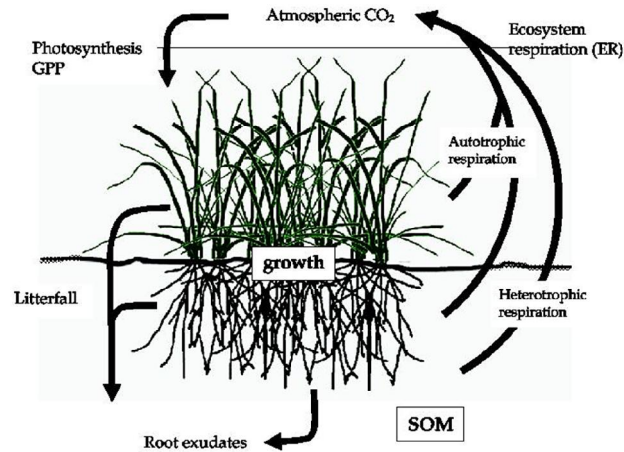
metabolizable organic carbon (Wrage *et al.*, 2001). The relative importance of these processes in N<sub>2</sub>O emissions from the soil is difficult to assess, and is likely to vary appreciably with the type of N fertilizer, land management, climate and other factors affecting soil conditions (Pathak, 1999). Chen *et al.*, (2002) indicated that the addition of fertilizer N significantly increased the NO<sub>3</sub>-N concentration in crops and enhanced the N<sub>2</sub>O emissions from crop-soil systems. Nitrifier denitrification contributes to the development of N<sub>2</sub>O and also causes losses of N fertilizer in agricultural soils (Wrage *et al.*, 2001).

## **2.5 Soil carbon of agricultural land**

### **2.5.1 Soil Organic Carbon**

Soils contain carbon in both organic and inorganic forms. In most soils (with the exception of calcareous soils) the majority of carbon is held as soil organic carbon (SOC). The term soil organic carbon refers to the carbon occurring in the soil in soil organic matter (SOM). The amount of SOC depends on soil texture, climate, vegetation and historical and current land use/management (Milne, 2008).

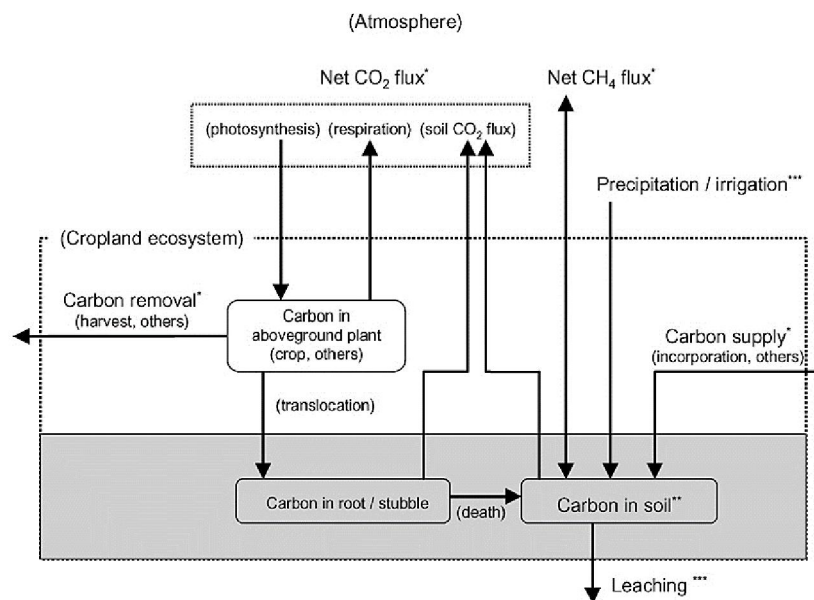
Soil organic carbon (SOC) consists of different carbon pools with the net turnover rates ranging from a few year to thousands of years (Amundson, 2001). The driving processes of the soil carbon cycle are carbon inputs from net primary productivity ( $NPP = GPP - \text{ecosystem respiration}$ ) and outputs by carbon decomposition (Figure 2.11) (Schädel and Luo, 2011). Organic matter is the products of NPP, which are transferred to soils in the form of litter, and presents the largest carbon input to the soils. Carbon output to the atmosphere is primarily driven by soil respiration (autotrophic and heterotrophic respiration) which is the second largest driver of carbon in the global carbon cycle.



**Figure 2.11** Schematic diagram of terrestrial ecosystem C processes. GPP, gross primary production, SOM, soil organic matter (Schädel and Luo, 2011)

### 2.5.2 Soil Carbon Budget and Sequestration

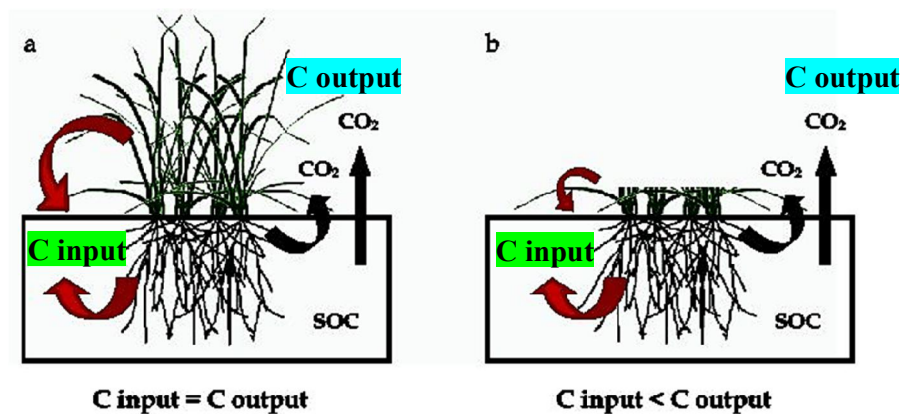
In crop land, the soil carbon budget (SCB) can be estimated by combining amounts of the net carbon supply and removal (Figure 2.12). The carbon is supplied to the soil as a root exudates, roots and stubble residue, and organic matter incorporation. Carbon content in the soil is lost by gaseous emissions of  $\text{CO}_2$  and  $\text{CH}_4$  (Nishimura *et al.*, 2008).



**Figure 2.12** Schematic diagram of carbon dynamics in cropland ecosystems (Nishimura *et al.*, 2008)

Soil carbon sequestration is the process of transferring CO<sub>2</sub> from the atmosphere into the soil through crop residues and other organic matters, and in a form that is not immediately re-emitted. This sequestering of carbon helps off-set emissions from combustion of fossil fuel and other emitted carbon activities, although enhancing soil quality and long term agronomic productivity (Sundermeier *et al.*, 2005; Al-Kaisi, 2008).

The soil is a dynamic system of carbon input and output need to be balanced in order to maintain the soil organic carbon (SOC) pool at equilibrium (Figure 2.13a). If carbon input is lesser than carbon output, a lack of the SOC pool occurs, which can produce in large releases of CO<sub>2</sub> to the atmosphere (Figure 2.13b). Otherwise, if carbon input to the soil surpasses carbon output, extra SOC can be sequestered in soils. SOC is not only an important carbon sink in the terrestrial carbon budget, but it also powerfully influences soil fertility and soil quality which in return is required for plant growth (Lal, 2004; Schädel and Luo, 2011).



**Figure 2.13** Soil C dynamics for (a) a natural grassland and (b) a harvested field for biofuel feedstock (Schädel and Luo, 2011)

Carbon sequestration through agricultural land has generated worldwide interest because of its potential impacts and benefits for agriculture and climate change. Agriculture conservation practices for example the use of different cropping and crop residue management, and organic management farming can improve soil carbon storage (Witt *et al.*, 2000; Lal, 2004; Chan, 2008; Kotal *et al.*, 2009; Saree *et al.*, 2012).

## 2.6 Effect of Crop rotations on greenhouse gas emissions, soil carbon change and crop yield

Crop rotation is one of the oldest and most basic agronomical practices (Castellazzi *et al.*, 2008). Wibberley (1996) pointed that a rotation is the sequence of crops grown in succession on a particular field. Crop rotation can extremely affect the amount of soil carbon lost from erosion by water (Unger and Mccalla, 1980).

Many literatures have described the different of crop rotations and management practices effect on greenhouse gas emissions. Nouchi and Yonemura (2005) studied the soil respiration of soybean and barley double cropping on CO<sub>2</sub> and CH<sub>4</sub> fluxes. They reported that soybean and barley double-cropping using conventional tillage showed lower carbon emission of 183 g C m<sup>-2</sup> y<sup>-1</sup> compared to the use of no-tillage cultivation. Wilson and Al-Kaisi (2008) studied the crop rotation and N fertilization effect on soil CO<sub>2</sub> emission in central Iowa. The results showed that increasing N fertilization generally decreased soil CO<sub>2</sub> emission and the continuous corn cropping system had higher soil CO<sub>2</sub> emission than the corn-soybean rotation. They indicated that cropping systems change can have immediate impact on cumulative soil CO<sub>2</sub> emissions, where continuous corn caused greater soil CO<sub>2</sub> emissions than corn soybean rotation. Moreover, Ramulu *et al.* (2009) studied the emission of N<sub>2</sub>O on crop rotation of horse gram-rice, black gram-rice, and green gram-rice in upland. They concluded that the N<sub>2</sub>O flux decreased in the order green gram > black gram > horse gram. During the fallow period from different pulses as well as rice cultivation the N<sub>2</sub>O emission was negligible. The seasonally integrated flux values of N<sub>2</sub>O during rice cultivation depended on rice cultivars and pulse types. Factor analysis showed that the emission of N<sub>2</sub>O mainly depended on soil nutrient N and organic matter contents.

Barton *et al.* (2013) presented influence of two crop rotation systems between lupin–wheat and wheat–wheat with liming management on GHG emissions from a semi-arid soil. They found that N<sub>2</sub>O fluxes were -1.4 to 9.2 g N<sub>2</sub>O-N ha<sup>-1</sup> day<sup>-1</sup> which lower than those reported for arable soils in temperate climates. When averaged across liming treatment, total N<sub>2</sub>O emissions were approximately 0.1 kg N<sub>2</sub>O-N ha<sup>-1</sup> after two years for both lupin–wheat and wheat–wheat rotations. After two years, CH<sub>4</sub> uptake was lower from the wheat–wheat rotation (601 g CH<sub>4</sub>-C ha<sup>-1</sup>) than that from lupin–wheat rotations (967 g CH<sub>4</sub>-C ha<sup>-1</sup>). However, liming management in the wheat–wheat rotation treatment increased CH<sub>4</sub> uptake (1,078 g CH<sub>4</sub>-C ha<sup>-1</sup>) to a value similar to the lupin–wheat rotation.

The crop management and improvement of soil carbon is important for sustainable agriculture. Nishimura *et al.* (2008) studied the effects of the changing in land use from low land rice cultivation to upland crop cultivation on soil carbon budget (SCB). They found that the single cropping of lowland rice were positive SCB ( $79-137 \text{ g C m}^{-2} \text{ y}^{-1}$ ), which indicates the carbon accumulation in the soil, while the single cropping of upland rice and double cropping of soybean and wheat plots were negative SCBs ( $-343$  to  $-275 \text{ g C m}^{-2} \text{ y}^{-1}$  and  $-361$  to  $-256 \text{ g C m}^{-2} \text{ season}^{-1}$ , respectively), which indicate the carbon loss from the soil. Kukul *et al.*, (2009) reported that the cropping system and soil type influenced crop biomass under different fertilizer application. The soil organic carbon (SOC) storages in rotation of rice–wheat were 54% and 30% higher in farmyard manure and NPK plots, respectively, than that in rotation of maize–wheat. Improved SOC content enhances soil quality, reduces soil erosion and degradation, and increases soil fertility. The soils in rotation of rice–wheat sequestered 55% higher SOC in farmyard manure plots and 70 % higher in NPK plots than that in rotation of maize–wheat.

The crop rotation practices have supported sustainable crop production and soil quality over time by structuring the temporal succession of crops in the fields (Castellazzi *et al.*, 2008). Gangwar *et al.* (2006) observed the different tillage and crop residue management in wheat cropping after rice cropping in sandy loam soils of Indo-Gangetic plain of India. They found that reducing tillage was significantly higher mean wheat yield ( $5.10 \text{ Mg ha}^{-1}$ ) compared to conventional ( $4.60 \text{ Mg ha}^{-1}$ ) and zero tillage ( $4.75 \text{ Mg ha}^{-1}$ ). Crop residue incorporation caused in highest mean yield ( $5.86 \text{ Mg ha}^{-1}$ ) during the third year. The highest mean yield ( $6.1 \text{ Mg ha}^{-1}$ ) was found in reduced tillage followed by conventional tillage ( $5.8 \text{ Mg ha}^{-1}$ ) under incorporated crop residue in the third year. The residue incorporation increased SOC and available P, while higher available K was observed in burning treatment during the third year. They suggested that reduced tillage and in situ incorporation of crop residues at the rate of  $5 \text{ Mg ha}^{-1}$  along with  $150 \text{ kg N ha}^{-1}$  in soils were optimal to achieve higher yield of wheat cropping after rice cropping.

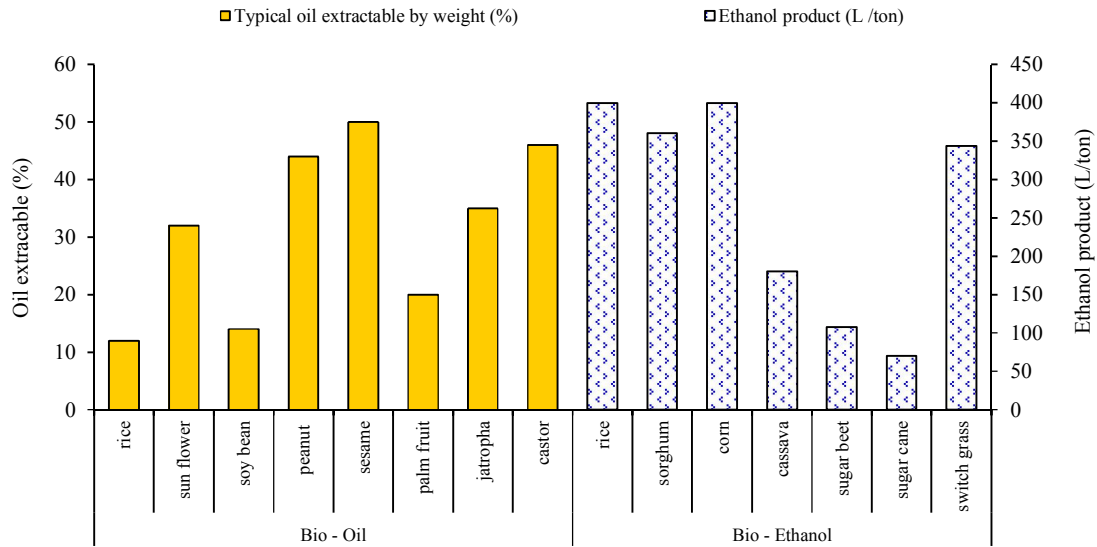
## 2.7 Energy crops

An energy crop is a plant grown used to make bio-fuels, such as bio-diesel and bio-ethanol (Figure 2.14), or combusted for its energy content to generate electricity or heat (Wikipedia, 2012). Szulczyk *et al.* (2010) pointed the advantage of biofuel production in helping reduced greenhouse gas emissions. Moreover, Schmitt *et al.* (2008) found that the use of corn to produce ethanol reduced the GHG emission 19% when compared to gasoline. Biofuel would reduce the reliance on petroleum oil, decrease the dependence on oil producing countries, and improve farmers' incomes (Szulczyk *et al.*, 2010). The use of crops to produce biofuel can compete with the food supply and increase their prices. For instance in the US, the price of corn grain almost doubled over the last 10 years partially because of the increasing interest in producing bioethanol (Holou, 2010).

The food and non-food energy crops might be used to produce various biofuels. Feedstocks for biodiesel include rice, sunflower, soybean, peanut, sesame, palm oil, jatropha, castor and other. Bio-diesel can be used in any diesel engine when mixed with mineral diesel. In EU, bio-diesel production from energy crops has grown gradually in the last decade, mainly focused on rapeseed used for oil and energy. Production of oil or bio-diesel from rape covers more than 12,000 km<sup>2</sup> in Germany, and become twice in the past 15 years. The typical yield of oil as pure bio-diesel is over 100,000 L/km<sup>2</sup>. Production bio-diesel crops economically attractive provided that sustainable crop rotations exist that are nutrient-balanced (Umer, 2011; Wikipedia, 2012).

A wide variety of feedstocks are used to produce bioethanol including rice, corn, sweet sorghum, switchgrass, sugarcane, sugar beet, and cassava (Figure 2.14). In Brazil, bioethanol is mostly made from sugarcane (Gnansounou *et al.*, 2005), whereas in the US, corn is currently the main feedstock used. Ethanol can be used in petrol engines as a replacement for gasoline. It can be mixed with gasoline to any percentage.

## Bio-Energy Products



**Figure 2.14** Bio-fuels products (Umer, 2011; Wikipedia, 2012)

### 2.7.1 Corn

Corn is the main feedstock used for producing ethanol fuel in the United States. Corn grain is rich in starch that can be converted into ethanol. There are two main methods to process starch into bioethanol include the wet milling process and the dry milling process (Reff. in Holou, 2010).

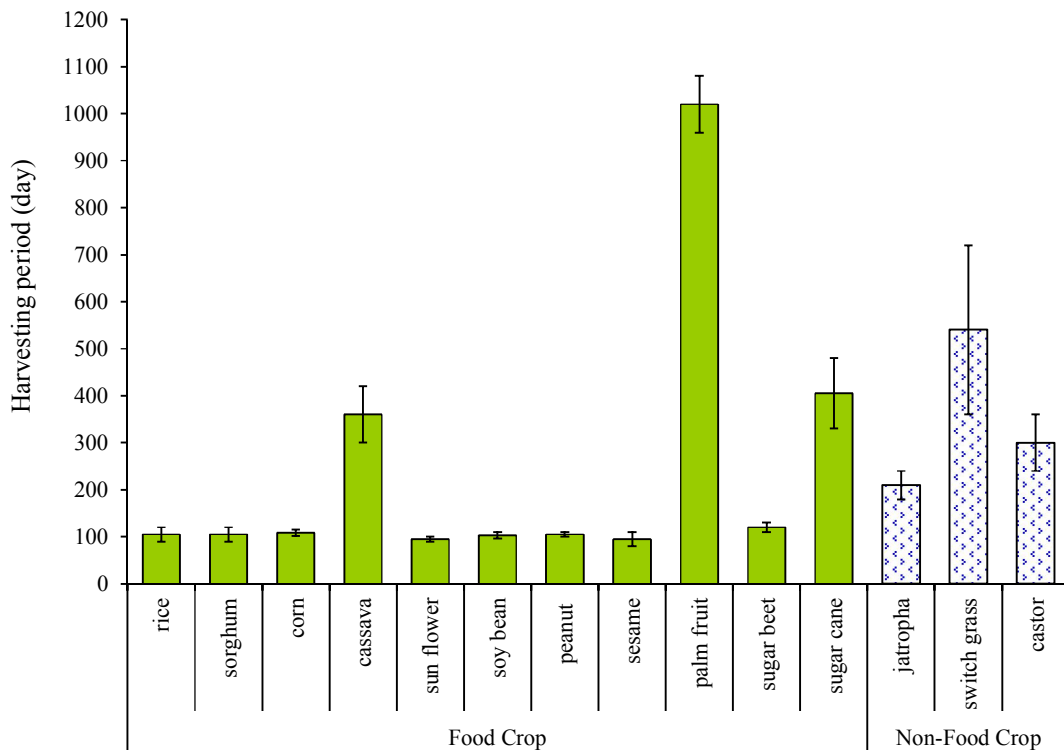
In Thailand, corn is one of the upland crops is often grown as part of a rice-based cropping system, because it has a short growing period (Figure 2.15) and a lower water requirement than that in rice cultivation (Figure 2.16) (DOAE, 2009; OAE, 2010). Corn can be grown in areas where irrigation water is available during the dry season. After the main rice crop is harvested, the corn crop should be planted as soon as possible (Boonpradub, 2003).

### 2.7.2 Sweet sorghum

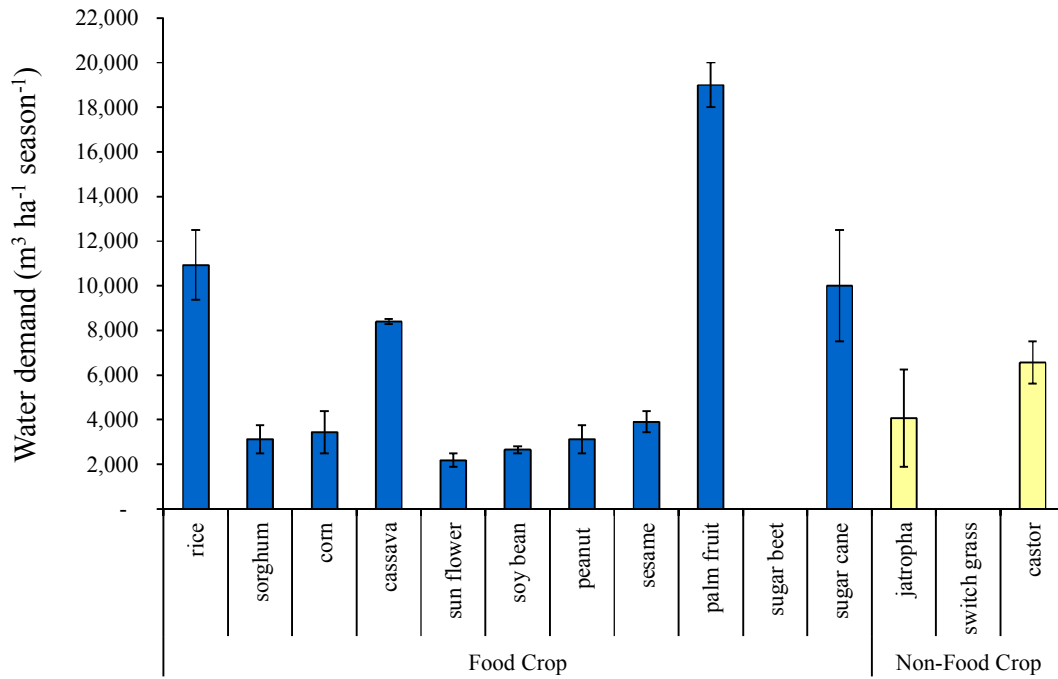
Sweet sorghum is a sugar crop, similar to sugar cane and sugar beets that may show promise as a source of sugar for ethanol fermentation. Biofuel from sweet sorghum can be produced from the sugary juice, the leaves, and even from bagasse (Sipos *et al.*, 2009; Stevens and Holou, 2010). The sugars from sweet sorghum are already free in the juice and ready to be fermented into ethanol (Stevens and Holou, 2010).

Sweet sorghum is a C4 plant, characterized by a high photosynthetic activity. It grows well and quickly in tropical and temperate regions. Sweet sorghum has a short growing cycle (90-120 days) (Figure 2.15) leading to the possibility of having more than one crop per year or rotation with other crops. Sweet sorghum has low water use (2,500-3,750 m<sup>3</sup> ha<sup>-1</sup> season<sup>-1</sup>) (see Figure 2.16). This plant is resistant to drought, salinity and flooding. Sweet sorghum is produced for its sugary juice. The sugar content in the sweet sorghum juice varied between 10 to 25 °Brix. The sugar yield from sweet sorghum varied between 1.6 and 13.2 Mg ha<sup>-1</sup>, with significant variations observed between years and regions (Reff. in Holou, 2010).

In Thailand, the growing period of sweet sorghum cv. K KU 40 is only 90–100 days (Jaisil *et al.*, 2009), therefore it can be planted for 3 cycles/year with an average yield of 30 tons/hectare/round and become 90 tons/hectare/year, whereas sugarcane able to cultivated for only one round/year and become 63 tons/hectare/year (Sridee *et al.*, 2011).



**Figure 2.15** Harvesting period of energy crops (DOAE, 2009; OAE, 2010)



**Figure 2.16** Water demand of energy crops (DOAE, 2009)

## 2.8 DNDC model and application

The DNDC (DeNitrification-DeComposition) model is a computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems (Li *et al.*, 1994). The DNDC model includes two components (see Figure 2.17). The first component consists of the soil climate, crop growth, and decomposition sub-models, predicts soil temperature, moisture, pH, Eh, and substrate concentration profiles based on ecological drivers (e.g., climate, soil, vegetation, and anthropogenic activity). The second component consists of the nitrification, denitrification, and fermentation sub-models, predicts  $\text{NH}_3$ ,  $\text{NO}$ ,  $\text{N}_2\text{O}$ , and  $\text{CH}_4$  fluxes based on the soil environmental variables (Li, 2000).

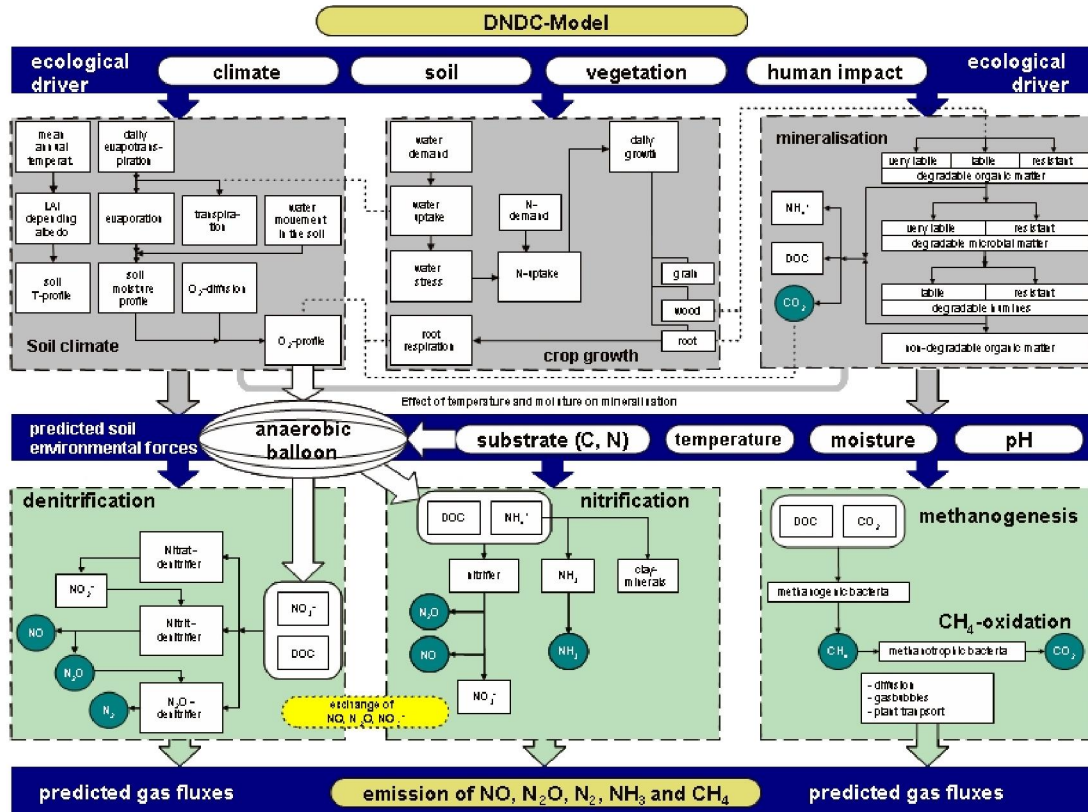


Figure 2.17 The components of DNDC model (Li *et al.*, 1994; Li, 2000)

The DNDC model is widely used to simulate greenhouse gas emissions. Smakgahn (2003) used a regional mode of the DNDC model to estimate CH<sub>4</sub> and N<sub>2</sub>O emissions from rice fields in Thailand. The simulated CH<sub>4</sub> emissions from single rice cultivation under continuously flooded management were 2.2-2.4 Tg CH<sub>4</sub>-C year<sup>-1</sup>. Simulated results of nitrous oxide emissions were 73.2-108.8 Mg N<sub>2</sub>O-N year<sup>-1</sup>. Qiu *et al.*, (2009) studied modeling impacts of carbon sequestration on net GHG emissions from agricultural soil in China. They investigated how the carbon sequestration strategies could affect N<sub>2</sub>O and CH<sub>4</sub> emissions from the agricultural soils in six selected sites across China. Model results indicated that; 1) when the different management practices were employed carbon sequestration rates increased, N<sub>2</sub>O or CH<sub>4</sub> emissions were also increased for these practices; and 2) reducing the rates of fertilizer application with the alternative practices could decrease N<sub>2</sub>O emissions while at the same time maintaining existing crop yields and C sequestration rates. The model approach can help with development of spatially differentiated best management practices at large regional scales. Abdalla *et al.* (2009) also assessed the

applicability of the field DNDC model. In the case of the arable field in Irish agriculture, simulated fluxes of  $\text{N}_2\text{O}$  agreed well with observed fluxes for medium to high fertilizer inputs (70–160 kg N  $\text{ha}^{-1}$ ), but poorly described those fluxes from zero fertilizer treatments. In terms of cumulated flux values, the relative deviation of the simulated fluxes from the measured values was a maximum of 6% for the highest nitrogen fertilizer inputs but increased to 30% for the medium nitrogen and more than 100% for the zero nitrogen fertilizer treatments.

Furthermore, the DNDC model is usually used for estimating SOC storage. In Chinese cropland, Tang *et al.* (2006) estimated soil organic carbon storage and identify its changing trends under current cropping systems. DNDC model was applied to predict SOC dynamics at 0-30 cm soil layer of agricultural ecosystems at national scale. The model results revealed the total SOC storage in cropland in China is around 3,968 Tg C and SOC is lost at rate of 78.89 Tg C  $\text{year}^{-1}$ . Chinese cropland soils release 186 Tg C as  $\text{CO}_2$  into the atmosphere, and receive only 68 Tg C from crop residues annually. Also, Liu *et al.* (2006) studied changes of soil organic carbon in an intensively cultivated agricultural region by DNDC model in Quzhou County in North China Plain. The DNDC model was validated using sampling data from 68 sites around the county under generalized farm practices. Their simulated results indicated that the DNDC model delivers acceptable modeling results at county level. The changes in farming practices indicated a strong effect on soil carbon sequestration. Estimation of soil organic carbon in long-term was studied by Wang *et al.* (2008) under the present management conditions in northern sites by upland crops and southern sites by paddy rice. Modelled results indicated that during the simulated 20 years, the northern sites were also losing SOC at relatively high rates from -1,000 to 200 kg C  $\text{ha}^{-1} \text{yr}^{-1}$  and the southern sites had relatively stable SOC contents with varies from -70 to 26 kg C  $\text{ha}^{-1} \text{yr}^{-1}$ .

From many previous studies, it can be concluded that the land management by crop cultivations have influenced the greenhouse gases emissions and soil organic carbon changes in agricultural soil. They are driven by the biological and physical processes under crop management practices. The short-lived upland crops should be developed to rotation in rain-fed rice field. Therefore, the rotation of energy crop with rain-fed rice can be a good crop management for carbon storage into the soil.

## CHAPTER 3

### GREENHOUSE GAS EMISSIONS AND CROP YIELDS BY ENERGY CROP ROTATIONS IN RICE FIELDS

#### 3.1 Introduction

Agricultural sector is the largest contributor to global anthropogenic non-CO<sub>2</sub> greenhouse gases (GHGs) which were 5.2-5.8 Gt CO<sub>2</sub>eq year<sup>-1</sup> or 10-12% of global anthropogenic emissions in 2010. The rice cultivation alone emitted 493-723 Mt CO<sub>2</sub> eq year<sup>-1</sup> (FAOSTAT, 2013; IPCC, 2014). In Thailand, agricultural emissions make up more than 22% (51.88 Mt CO<sub>2</sub>eq) of annual GHG emissions which were 57.7% from rice cultivation (ONEP, 2010). Rice is the most important crop in Thailand, which cover almost 50% of the cultivation areas. An accounting 60% is the rain-fed rice cultivation (LDD, 2010).

Many publications have reported that GHG emissions from rice cultivation can mitigate by crop management practices, for example, water management by mid-season drainage (Cai *et al.*, 1997; Lu *et al.*, 2000; Siriratpiriya and Pradubsuk, 2002; Towprayoon *et al.*, 2005; Xu and Hosen, 2010), organic matter, crop residue and fertilizer managements (Jernsawatdipong *et al.*, 1994; Cai *et al.*, 1997; Bossio *et al.*, 1999; Khalil and Shearer, 2006; Xu and Hosen, 2010), and managed by the crop rotation (Zou *et al.*, 2004; Nishimura *et al.*, 2008; Datta *et al.*, 2011).

Crop rotation in rice field can improve utilization of agricultural land, however different crop systems have shown different effects on GHG emissions (Adhya *et al.*, 2000; Zheng *et al.*, 2000; Nishimura *et al.*, 2008; Datta *et al.*, 2011; Zhou *et al.*, 2014). In flooded rice cultivation, CH<sub>4</sub> is produced in anaerobic zones of submerged soils by methanogens and emitted to the atmosphere mainly through the rice plant. Generally, CH<sub>4</sub> is emitted from rice plants to the atmosphere via three pathways; diffusion, ebullition and plant-mediated transport. In upland crop, CH<sub>4</sub> is oxidized into CO<sub>2</sub> by methanotrophs in the aerobic zones during upland crop season (Le Mer and Roger, 2001). Agricultural soil management activities such as chemical fertilizer or manure application are the main source of N<sub>2</sub>O emission by Nitri-Denitrification process (Lal, 2007; Nishimura *et al.*, 2008). In crop land, plants are uptake carbon dioxide (CO<sub>2</sub>) by photosynthesis in biomass form (seed, leaf, stem, and root) and releases CO<sub>2</sub> by respiration.

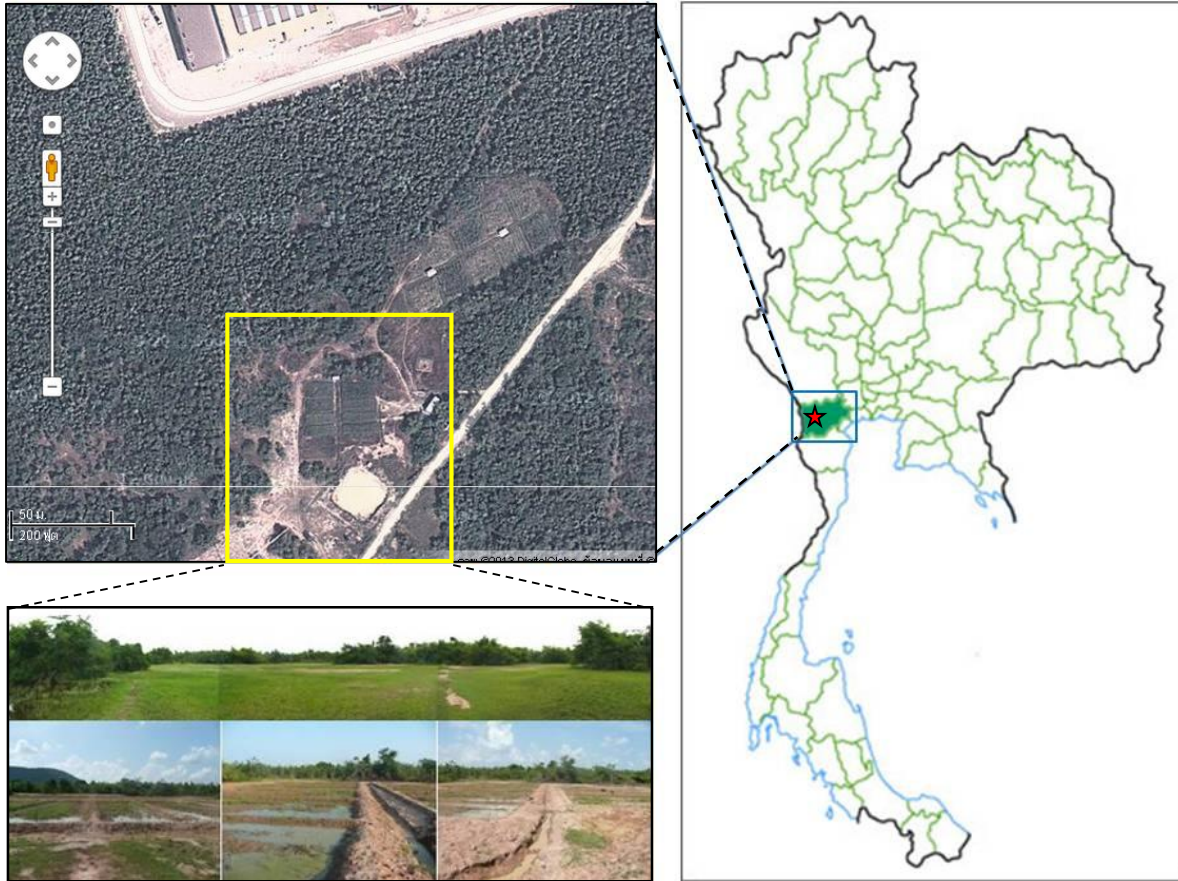
Recently, the increasing in bio-energy tends to increase. There is considerable interest in the short period crop rotation with fast growing crops for bio-energy production. The energy crops such as corn and sweet sorghum are the short growing period crops (about four months), low water demand, drought resistance and well feedstocks for bio-ethanol production (Ban *et al.*, 2008; Holou, 2010; Wu *et al.*, 2010). Therefore, this study introduced the field experiment of their energy crops rotation in rain-fed rice field, and studied the effects of different crop rotation systems on greenhouse gas emissions and crop yields.

## 3.2 Methodology

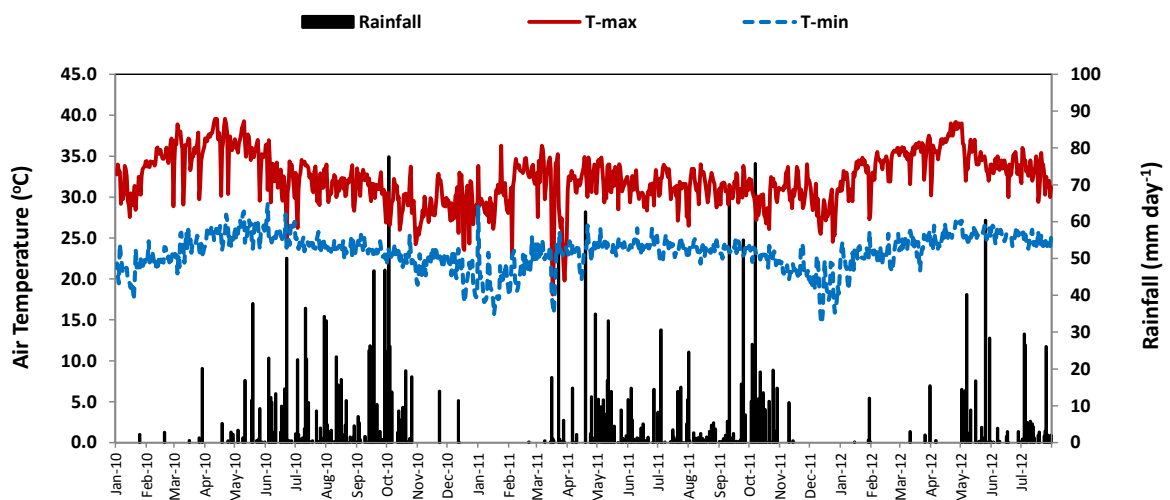
### 3.2.1 Site description

The field experiment was carried out at King Mongkut's University of Technology Thonburi, Ratchaburi Campus (13°35' N, 99°30' E) in Rang Bua, Chombung District, Ratchaburi Province, Thailand (Figure 3.1). An abandoned rice field that had laid fallow for 10 years before the experiments began in 2010. The soil at this site is classified as Khao Yoi (Kyo) soil series described as follows: a pinkish gray (7.5YR6/2) sandy loam, many fine distinct strong brown mottles, weak medium and coarse subangular blocky structure, soft, friable, slightly sticky, slightly plastic, and very few small soft Fe and Mn nodules. The total Fe content was 3.842-77.34 g kg<sup>-1</sup> and the total Mn content was 0.08-3.09 g kg<sup>-1</sup> (Churthong, 2009). Other soil characteristics are as follows: 53% sand, 45% silt and 2% clay, pH 5.8, 1.75 g cm<sup>-3</sup> bulk density, and 0.69% total organic carbon content.

Air temperatures and rainfall data (see Figure 3.2) during the experimental periods were collected from the Dry Dipterocarp Forest Site at KMUTT Ratchaburi station, which is 400 m away from our experimental site. Annual rainfall in 2010 and 2011 were 1,063 mm and 1,022 mm, respectively. The maximum monthly rainfall amounts were 243.4 mm in October 2010 and 256.9 mm in October 2011. Mean air temperatures in 2010 and 2011 were 27.9 °C and 26.7 °C, respectively. The average maximum air temperature was 39.6 °C in 2010 and 36.3 °C in 2011. The average minimum air temperature was 14.6 °C in 2011 and 17.1 °C in 2010 (Sanwangsri *et al.*, 2011). In 2012, weather data showed in Jan-July which was duration of energy crop experiment. The average maximum air temperature was 39.2 °C in April.



**Figure 3.1** Ratchaburi Province Map and location of study site



**Figure 3.2** Daily air temperatures and rainfall (Jan 2010-Jul 2012) from the Dry Dipterocarp Forest Site at KMUTT, Ratchaburi Campus

### 3.2.2 Field experimental design

The major part of rice cultivation in Thailand is rain-fed, and accounts for 60% of rice cultivated areas. From this condition, we designed the rice for main crop in the rainy season (Aug-Dec 2010 and 2011) and rotated energy crop in the dry season (Feb-Jun in 2010, 2011 and 2012) (Figure 3.3). Corn and sweet sorghum were selected for rotation in rice field because there are short growing period (about 4 months), requires less water, resistant in the dry weather condition, and feedstock for ethanol production (OAE, 2008; Suraphong Chareunrat, 2008).

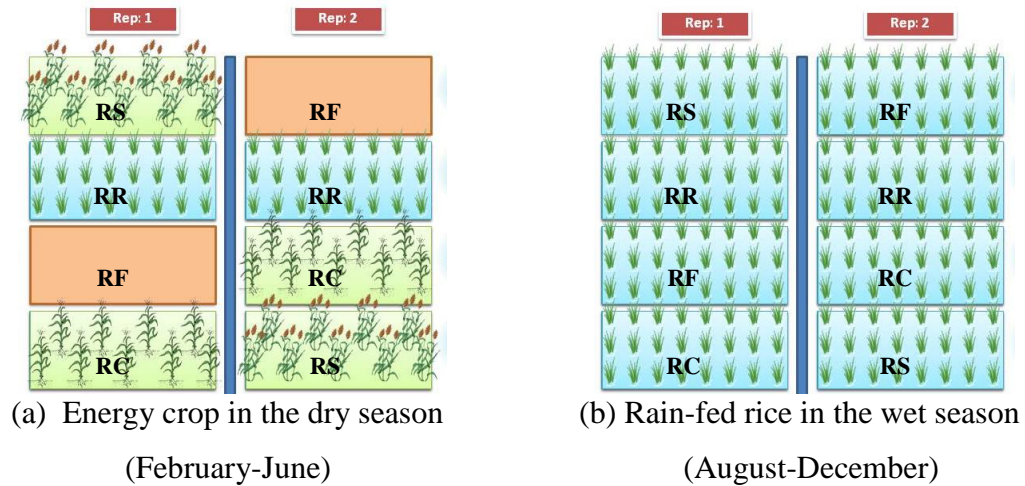
This experiment was investigated in four treatments:

- 1) fallow land in the dry season and rain-fed rice in the wet season (RF), which is the treatment in the local conventional farmer's practices,
- 2) irrigated rice in the dry season and rain-fed rice in the wet season (RR),
- 3) irrigated corn (maize) in the dry season rotated with rain-fed rice in the wet season (RC), and
- 4) irrigated sweet sorghum in the dry season rotated with rain-fed rice in the wet season (RS) during the 2010-2012 cropping periods.

The experiment was laid out in a randomized block design with eight plots (5 m × 15 m) in two replications (Figure 3.4).

Year	2010												2011												2012						
Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
RF	Fallow land						Rain-fed rice						Fallow land						Rain-fed rice						Fallow land						
RR	Irrigated rice			Rain-fed rice			Rain-fed rice			Rain-fed rice			Irrigated rice																		
RC	Corn				Rain-fed rice				Corn				Rain-fed rice				Corn														
RS	Sweet sorghum				Rain-fed rice				Sweet sorghum				Rain-fed rice				Sweet sorghum														

**Figure 3.3** Field experimental designs for four treatments in 2010-2012



**Figure 3.4** Diagram of the crop experiment plots

The crop cultivars in this study were Pathumthani 1 rice, Suwan 5 corn and Khon Kaen 40 sweet sorghum. Details of different crop management practices are listed in Table 3.1. Tillage was done two times at a plowing depth of 20 cm during land preparation and 5 cm during seeding/planting time in all field plots. The crop residues include above ground residue (leaves and stem) and below ground residue (root) were incorporated into the field before next crop cultivation. The dried cow manure (C=24%, N=1.18%, C/N=13) was applied for soil amendment in year 2010, which was incorporated at the rate of 4.3 ton ha<sup>-1</sup> for the first crop and 10 ton ha<sup>-1</sup> for the second crop. The application rate of N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O (15:15:15) compound fertilizer as basal fertilizer was 156 kg ha<sup>-1</sup> for rice, corn and sweet sorghum. Urea (46:0:0) were used for top dressing by 125 kg ha<sup>-1</sup> for rice and 156 kg ha<sup>-1</sup> for corn and sweet sorghum cultivation. Water management in rice field was continuously flooded with approximately 10 cm of surface water depth.

According to the conventional practice, rice was planted by direct sowing at a seed rate of 95 kg ha<sup>-1</sup> (Figure 3.5(a)). Corn and sweet sorghum were planted by direct seeding at a spacing of 75 cm × 25 cm for corn and 50 cm × 10 cm for sorghum. The crops of corn and sweet sorghum were irrigated twice a week by sprinkler (Figure 3.5(b))

**Table 3.1** Crop management practices of rice and energy crop cultivation in KMUTT's experimental site

Items	2010	2011	2012	
<b>Tillage</b>	01/02: Plow depth of 20 cm	01/22: Plow depth of 20 cm	01/29: Plow depth of 20 cm	
	02/07: Ploughing slightly, 5 cm	01/29: Ploughing slightly, 5 cm	02/19: Ploughing slightly, 5 cm	
	07/09: Plow depth of 20 cm	07/23: Plow depth of 20 cm		
	08/14: Ploughing slightly, 5 cm	08/28: Ploughing slightly, 5 cm		
<b>Manure application</b>	01/02: incorporated cow manure (4.3 ton ha <sup>-1</sup> )	No application	No application	
	07/09: incorporated cow manure (10 ton ha <sup>-1</sup> )			
<b>Crop residue incorporation</b>				
Dry season:	Corn	No crop residue	01/22: rice residue 9.8 ton/ha	01/29: rice residue 9.0 ton/ha
	Sorghum	No crop residue	01/22: rice residue 10.7 ton/ha	01/29: rice residue 9.7 ton/ha
	Rice	No crop residue	01/22: rice residue 9.9 ton/ha	01/29: rice residue 8.2 ton/ha
	Fallow	No crop residue	01/22: rice residue 10.1 ton/ha	01/29: rice residue 7.3 ton/ha
Wet season:	Rice after corn	07/09: corn residue 1 ton/ha	07/23: corn residue 10.5 ton/ha	
	Rice after sorghum	07/09: sorghum residue 2.5 ton/ha	07/23: sorghum residue 5.72 ton/ha	
	Rice after rice	07/09: rice residue 10.4 ton/ha	07/23: rice residue 9.4 ton/ha	
	Rice after fallow	07/09: no crop residue	07/23: no crop residue	

01/02 is month/date of crop management practices.

**Table 3.1** Crop management practices of rice and energy crop cultivation in KMUTT’s experimental site (Cont’)

Items		2010	2011	2012	
<b>Crop cultivation</b>					
Dry season:	Corn	03/18: planting, 05/31: harvest	01/29: planting, 05/10: harvest	02/19: planting, 06/08: harvest	
	Sorghum	02/10: planting, 06/10: harvest	01/29: planting, 05/22: harvest	02/19: planting, 06/08: harvest	
	Rice	02/07: sowing, 06/26: harvest	01/29: sowing, 06/24: harvest	02/19: sowing, 07/01: harvest	
	<hr/>				
	Wet season:	Rice after corn			
		Rice after sorghum	08/14: sowing,	08/28: sowing,	
Rice after rice		12/18: harvest	12/28: harvest		
Rice after fallow					

01/02 is month/date of planting and harvest.

**Table 3.1** Crop management practices of rice and energy crop cultivation in KMUTT’s experimental site (Cont’)

Items	2010	2011	2012
<b>Fertilizer application</b>			
Dry season:	Corn	03/24: NPK (156 kg /ha) 04/12: Urea (156 kg /ha)	03/20: NPK (78 kg/ha)+Urea (12.5 kg/ha) 04/09: Urea (156 kg /ha)
	Sorghum	03/12: NPK (78 kg/ha)+Urea (12.5 kg/ha) 04/07: Urea (156 kg /ha)	03/20: NPK (78 kg/ha)+Urea (12.5 kg/ha) 04/09: Urea (156 kg /ha)
	Rice	03/12: NPK (156 kg /ha) 04/07: Urea (125 kg /ha)	02/25: NPK (156 kg /ha) 04/09: NPK (78 kg/ha)+Urea (12.5 kg/ha), 05/23: Urea (125 kg /ha)
			04/01: NPK (156 kg /ha) 04/24: NPK (78 kg/ha)+Urea (12.5 kg/ha)
			04/01: NPK (156 kg /ha) 04/24: NPK (78 kg/ha)+Urea (12.5 kg/ha)
			04/01: NPK (156 kg /ha) 04/24: NPK (78 kg/ha)+Urea (12.5 kg/ha)
Wet season:	Rice after corn		
	Rice after sorghum	09/07: NPK (156 kg /ha)	10/09: NPK (156 kg /ha)
	Rice after rice	11/11: Urea (125 kg /ha)	11/20: Urea (125 kg /ha)
	Rice after fallow		

01/02 is month/date of fertilizer application.

The compound fertilizer NPK is a combination of N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O by percentage 15:15:15.

Urea is 46:0:0 of nutrient (NPK) contents.

**Table 3.1** Crop management practices of rice and energy crop cultivation in KMUTT’s experimental site (Cont’)

Items	2010	2011	2012
<b>Flooding for Rice cultivation</b>			
Dry season: Rice	02/05 - 02/08	01/27 - 01/30	02/11 - 02/20
	03/11 - 06/10	02/20 - 06/09	03/02 - 06/09
	continuously flooding, 10 cm	continuously flooding, 10 cm	continuously flooding, 10 cm
Wet season: Rice	08/13 - 08/16	08/19 - 08/22	
	09/01 – 12/10	09/03 – 12/16	
	continuously flooding, 10 cm	continuously flooding, 10 cm	
<b>Water supply for crop cultivation</b>			
Dry season:	Corn	900 m <sup>3</sup> /ha/crop	
	Sorghum	800 m <sup>3</sup> /ha/crop	
	Rice	1,500 m <sup>3</sup> /ha/crop	
	Fallow	-	
Wet season:	Rain-fed rice	600 m <sup>3</sup> /ha/crop	

01/02 is month/date of flooding period.

The water for these crop cultivations was supplied from the pond at the experimental field.



(a) Rice cultivation



(b) Energy crop cultivation

**Figure 3.5** Rice and energy crop cultivation practices

In the field experiment, the energy crop was rotated in the dry season (Feb-Jun in 2010, 2011 and 2012) and rain-fed rice cultivated in wet season (Aug-Dec in 2010 and 2011). The crop cultivation sequence was five cropping in two and a half years. The first, third and fifth crops started with the irrigated rice, corn, and sweet sorghum in RR, RC and RS treatments, respectively. The second and fourth crops cultivated with rain fed rice in all treatments (Figure 3.6).



(a) First crop in dry season, 2010



(b) Second crop in wet season, 2010



(c) Third crop in dry season, 2011



(d) Fourth crop in wet season, 2011



(e) Fifth crop in dry season, 2012

**Figure 3.6** The five continuous crop cultivations in 2010-2012

### 3.2.3 Greenhouse gas sampling, analysis and calculation

#### 3.2.3.1 Greenhouse gas sampling technique

Sampling of the gas emitted from the field was by the closed chamber method at three points in each plot. Access to these sampling points in plots where rice was growing was by stainless steel frame bridges 25 cm above the soil to avoid disturbing the rice field processes. (Figure 3.7 (a)). Each gas sampling chamber consisted of an acrylic cover resting on a stainless steel base 30 cm × 30 cm square open at the bottom, with sides 5 cm above the ground and 10 cm below the ground. Two cm diameter holes in each side of the base below the ground allowed water and nutrients to pass through the soil inside. The acrylic cover rested in a groove around the top of the square base filled with water as a gas seal. The height of the chamber was 15 cm placed between the crop rows for measured soil respiration, and 15-120 cm depending on the height of the plants inside for measured soil and plant respiration (Figure 3.7 (b)). The acrylic cover was black to stop photosynthesis in the plants during the gas sampling and was covered with white polystyrene foam sheet 1.5 cm thick for thermal insulation.



(a) Greenhouse gas sampling in rice field



(b) Greenhouse gas sampling in energy crop field

**Figure 3.7** Different chambers and stainless steel base for gas sampling

Gas samples were taken once a week between local times 09:00-15:00. Gas samples were taken from the headspace once a week with a 20 ml plastic syringe and transferred to evacuated vials (Figure 3.8(a)). Analysis of the gas in the vials was made

within 24 hours in the laboratory as described following. During the fallow period and beginning of cropping the samples were taken at 0, 10, 20 and 30 minutes after putting the closed chamber over the sampling point. During the plant-growing period the samples were taken at 0, 5, 10 and 15 minutes. Samples were taken from four of the plots with different dry season treatments in the morning and from the other four plots in the afternoon.

The temperature inside the chamber was measured with a thermometer at every sampling time (Figure 3.8(b)). In the rice cultivation period the redox potential (Eh) in the soil was automatically recorded every minute for 20 minutes during the sampling time using an ion selective electrode (pH/ORP combination sensor, YSI Professional Plus, USA) at a depth of 10 cm near the chamber (Figure 3.8(c)).

### 3.2.3.2 Greenhouse gas analysis

The gas samples were analyzed for CH<sub>4</sub> and CO<sub>2</sub> by gas chromatography (Shimadzu GC-2014, Japan) with a flame ionization detector (FID) and Unibead C Packed column with methanizer (Shimadzu MTN-1, Japan) (Figure 3.8(d)). The temperatures of the column, injector and detector were maintained at 150, 120 and 300°C, respectively. Helium was used as carrier gas with a flow rate of 50 ml min<sup>-1</sup>. N<sub>2</sub>O was analyzed by gas chromatography (Shimadzu GC-14B, Japan) with an electron capture detector (ECD) and Poropak column. The column, injector and detector temperatures were set at 65, 150 and 300°C, respectively.



(a) Gas sample transfer



(b) Measuring chamber height and temperature inside



(c) Measuring soil Eh



(d) Gas chromatography

**Figure 3.8** Greenhouse gas sampling, rice field site measuring and gas chromatography

### 3.2.3.3 Greenhouse gas flux calculations

The gas emissions were expressed in terms of mass per unit area per unit of time. The fluxes of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> were calculated using the linear portion of the gas concentration change inside the chamber over sampling time, as step calculation from equation (1) (Nishimura *et al.*, 2008). CO<sub>2</sub> emission from this study was determined as soil heterotrophic respiration during fallow period and ecosystem respiration (plant dark respiration and soil heterotrophic respiration) during crop growing period, since the chamber covered the plants while taking gas sample.

$$F = \frac{dC_i}{dt} \times \frac{1}{A} \times \frac{M_i PV}{RT} \times t_i \quad \dots\dots\dots(\text{Eq. 1})$$

where,  $F$  = the cumulative CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes (mg m<sup>-2</sup> hr<sup>-1</sup>)  
 $\frac{dC_i}{dt}$  = the increase/decrease rates of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O concentrations, respectively (ppm min<sup>-1</sup>)  
 $M_i$  = the mass number of CO<sub>2</sub> (44 x 10<sup>3</sup>), CH<sub>4</sub> (16 x 10<sup>3</sup>) and N<sub>2</sub>O (44 x 10<sup>3</sup>) (mg/mol)  
 $A$  = the area of the chamber (width x length) (m<sup>2</sup>)  
 $P$  = the atmospheric pressure (1 atm)  
 $V$  = the chamber volume (width x length x height) (m<sup>3</sup>)  
 $R$  = the gas constant (0.082058 x 10<sup>-3</sup> m<sup>3</sup>·atm mol<sup>-1</sup> K<sup>-1</sup>)  
 $T$  = the air temperature inside the chamber (K)  
 $t_i$  = time factor for 1 hr. (= 60 min)

The biological methane oxidation rates from the fallow land and the energy crop field were estimated from the first order rate constant multiplied by initial concentration of methane (Knief *et al.*, 2005), flowing equation (2);

$$R = k_1[\text{CH}_4]_0 \quad \dots\dots\dots(\text{Eq. 2})$$

where,  $R$  = methane oxidation rate (ppm CH<sub>4</sub> min<sup>-1</sup>)  
 $k_1$  = methane oxidation rate constant (min<sup>-1</sup>)  
 $[\text{CH}_4]_0$  = the initial methane concentration in headspace (ppm)

The methane oxidation rate constant ( $k_1$ ) was calculated from the decreasing of natural log of methane concentration with time as shown in equation (3).

$$\ln[\text{CH}_4]_t = -k_1t + \ln[\text{CH}_4]_0 \quad \dots\dots\dots(\text{Eq. 3})$$

where,  $[\text{CH}_4]_t$  = the headspace methane concentration at time t (ppm)  
 $[\text{CH}_4]_0$  = the initial methane concentration in the headspace (ppm)  
 t = sampling time (0, 5, 10 and 15 min)  
 $k_1$  = oxidation rate constant ( $\text{min}^{-1}$ )

Cumulative fluxes of  $\text{CH}_4$ ,  $\text{N}_2\text{O}$  and  $\text{CO}_2$  were calculated by plotting the daily fluxes through time, assuming linear changes in gas emissions between two successive sampling dates and integrating the resulting graph over the individual crop growth periods (Jantalia *et al.*, 2008).

Combined seasonal global warming potential (GWP) was calculated using Equation (4) (Nishimura *et al.*, 2005; IPCC, 2007):

$$\text{Combined GWP} = (\text{CH}_4 \text{ emit} \times 21) + (\text{N}_2\text{O} \text{ emit} \times 310 \times (44/28)) \dots\dots\dots(\text{Eq. 4})$$

where, Combined GWP = Global warming potential of  $\text{CH}_4 + \text{N}_2\text{O}$  ( $\text{g CO}_2 \text{ eq crop}^{-1}$ )  
 $\text{CH}_4 \text{ emit}$  = seasonal  $\text{CH}_4$  emission ( $\text{g CO}_2 \text{ eq crop}^{-1}$ )  
 $\text{N}_2\text{O} \text{ emit}$  = seasonal  $\text{N}_2\text{O}$  emission ( $\text{g CO}_2 \text{ eq crop}^{-1}$ )  
 21 and 310 = GWP of  $\text{CH}_4$  and  $\text{N}_2\text{O}$

### 3.2.4 Crop biomass sampling and analysis

The above ground biomass (grain and straw) and below ground (roots) were measured. The biomass of rice, corn and sweet sorghum were sampled at the crop harvest. Rice biomass was sampled inside the chamber ( $0.09 \text{ m}^2$ ) by removed with total of above and below ground (Figure 3.9 (a-b)). The rice yield components were estimated by harvesting an area of  $1 \text{ m}^2$  with three points in each plot (Figure 3.9 (c-d)). Corn and sweet sorghum were collected from the above and below ground existing with three points in each plot. The collected biomass samples were separated in three parts: grain, straw, and root. The each separated samples were packed in the bag and dried in an oven (redLINE RF53, Germany) (see Figure 3.10) at  $80^\circ\text{C}$  for 48 hrs to get dry weight and were then put through a cutting

mill (Retsch SM 2000, Germany) and ground to pass 0.5 mm sieve. Carbon content of biomass was analyzed with a nitrogen and carbon analyzer (CN Analyzer, CN Corder MT 700, Japan).

The sorghum juice extraction was done by a sorghum-cane juicer (Figure 3.11 (a)). The amounts of sugar in the juice of sweet sorghum were measured by sugar refractometer. Crop grain yields of sweet sorghum and corn were air dried (Figure 3.11 (b-c)). The conventional practices of rice harvesting in study field as shown in Figure 3.12.



(a) Sampling area ( $0.09 \text{ m}^2$ ) inside base chamber



(b) Rice samples inside chamber with above and below ground



(c) Quadrat sampling area ( $1 \text{ m}^2$ )



(d) Rice yield sampling

**Figure 3.9** Rice biomass sampling and rice yield sampling



(a) crop biomass packing  
(grain yield, straw (leaves+stem) and root)



(b) Forced Air Convection Drying Oven,  
redLINE RF53, Germany

**Figure 3.10** Crop biomass packing and air drying oven



(a) juice extraction



(b) grain sorghum



(c) grain corn

**Figure 3.11** Juice extraction and sweet sorghum and corn yields



**Figure 3.12** Conventional practices of rice harvest

### 3.3 Results

Under the different four crop rotation systems in the field experiment, the results are presented in the seasonal trends and cumulative CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> fluxes, the seasonal and annual non-CO<sub>2</sub> emissions which combined CH<sub>4</sub> and N<sub>2</sub>O into CO<sub>2</sub> equivalent, the components of crop yields, the amounts of greenhouse emission on rice production and also the economic estimation. These results are described below.

#### 3.3.1 Seasonal fluxes trends and gas cumulative of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> fluxes

Seasonal trends of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> fluxes under different crop rotation systems with (a) fallow-rice (RF), (b) rice-rice (RR), (c) corn-rice (RC) and (d) sorghum-rice (RS) from Jan 2010 to Jul 2012 are presented in Figures 3.13-3.15. Horizontal arrows in (a) to (d) show the crop cultivation periods. Vertical arrows in all treatments show the fertilizer application. The broken line in CH<sub>4</sub> fluxes (Figure 3.13) show the redox potential (Eh) in rice cultivation period. Solid and broken horizontal bars at the bottom show continuously and intermittently flooded periods in the rice crop season. The broken lines in CO<sub>2</sub> fluxes (Figure 3.15) show the plant height. The error bars are indicated the standard deviations of six chambers per two replications in each rotation systems.

##### 3.3.1.1 Seasonal trends and cumulative of CH<sub>4</sub> fluxes

The seasonal trends of CH<sub>4</sub> fluxes and soil redox potential (Eh) during the rice growing period are presented in Figure 3.13. CH<sub>4</sub> fluxes in all treatments were found to be significant only during the rice growing season but were negligible during the fallow period (RF) and during the dry season when corn (RC) and sweet sorghum (RS) were cultivated. CH<sub>4</sub> flux peaked while the soil Eh decreased around two weeks after rice sowing. The CH<sub>4</sub> flux usually increased after flooding and decreased during water drainage before rice harvest. The highest CH<sub>4</sub> fluxes were observed in continuous rice cultivations (RR) treatment (Figure 3.13(b)).

The amounts of CH<sub>4</sub> emitted per season (crop) are given in Table 3.2. The cumulative CH<sub>4</sub> fluxes in the double cropping of rice (RR) were highest, varying from 18.29-120.42 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>. In the rotation with corn and sweet sorghum, the cumulative CH<sub>4</sub> fluxes were low. These amounts varies from -0.50 mg CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup> to 2.72 mg CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>. The annual cumulative CH<sub>4</sub> fluxes (two crops combined) are shown in Table 3.3. The RR treatment in both of year 2010 (893.49 kg CH<sub>4</sub> ha<sup>-1</sup> y<sup>-1</sup>) and 2011 (1,788.26 kg CH<sub>4</sub> ha<sup>-1</sup> y<sup>-1</sup>) was significantly ( $p \leq 0.05$ ) higher than that for the RF, RC and RS treatments.

### 3.3.1.2 Seasonal trends and cumulative of N<sub>2</sub>O fluxes

N<sub>2</sub>O fluxes were observed during the fallow land, corn and sweet sorghum growing period (Figure 3.14). The highest N<sub>2</sub>O fluxes were significantly observed in crop of corn and sweet sorghum with total of plant and soil, especially in year 2011 and 2012. Relatively lower N<sub>2</sub>O fluxes were observed during the rice growing season in RR as compared to RC, RS and RF. After fertilizer application, the N<sub>2</sub>O fluxes significantly increased in all crops.

The seasonal cumulative fluxes of N<sub>2</sub>O in different cropping systems are given in Table 3.2. The N<sub>2</sub>O fluxes varied in the range 646.04-847.94 mg N<sub>2</sub>O m<sup>-2</sup> crop<sup>-1</sup> in the rotation with corn (RC) and 771.99-879.31 mg N<sub>2</sub>O m<sup>-2</sup> crop<sup>-1</sup> in the rotation with sweet sorghum (RS). The low fluxes of N<sub>2</sub>O in double cropping of rice (RR) have been in the range of 54.88-174.73 mg N<sub>2</sub>O m<sup>-2</sup> crop<sup>-1</sup>. The annual fluxes (Table 3.3) from RF, RC, RR and RS plots in year 2010 were 5.77, 7.77, 1.54 and 8.93 kg N<sub>2</sub>O ha<sup>-1</sup> y<sup>-1</sup>, respectively and in 2011 were 3.41, 9.01, 1.22 and 10.40 kg N<sub>2</sub>O ha<sup>-1</sup> y<sup>-1</sup>, respectively. In the energy crop treatment (corn and sweet sorghum), little difference in N<sub>2</sub>O flux was observed in 2010 and 2011.

### 3.3.1.3 Seasonal trends and cumulative of CO<sub>2</sub> fluxes (ecosystem respiration)

Fluxes of CO<sub>2</sub> were determined as soil heterotrophic respiration and the ecosystem respiration (plant and soil heterotrophic respiration) (Figure 3.15). The similar trends and low fluxes of CO<sub>2</sub> were found in soil heterotrophic respiration during fallow land and energy crop growing season. The seasonal of CO<sub>2</sub> fluxes continued increase from early stage until harvesting during crop growing season, as following the seasonal trends of plant growth. In the crop growing season of corn, and sweet sorghum, CO<sub>2</sub> fluxes were largely higher in the early stage and then stepped down, when crop plants were higher than the chamber. While in rice plant has been observed until harvest.

Under different crop cultivations (2.09-5.92 kg CO<sub>2</sub> m<sup>-2</sup> crop<sup>-1</sup>), the seasonal cumulative of CO<sub>2</sub> fluxes was higher than during the fallow period (0.59-1.91 kg CO<sub>2</sub> m<sup>-2</sup> crop<sup>-1</sup>) as presented in Table 3.2. In rain-fed rice season of years 2010 and 2011, the amount of CO<sub>2</sub> fluxes varies from 2.73 to 3.80 kg CO<sub>2</sub> m<sup>-2</sup> crop<sup>-1</sup>, with no significant difference. The annual CO<sub>2</sub> fluxes (Table 3.3) in year 2010 varies from 43.26 to 89.81 t CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup> and year 2011 varies from 53.20 to 90.45 t CO<sub>2</sub> ha<sup>-1</sup> y<sup>-1</sup>.

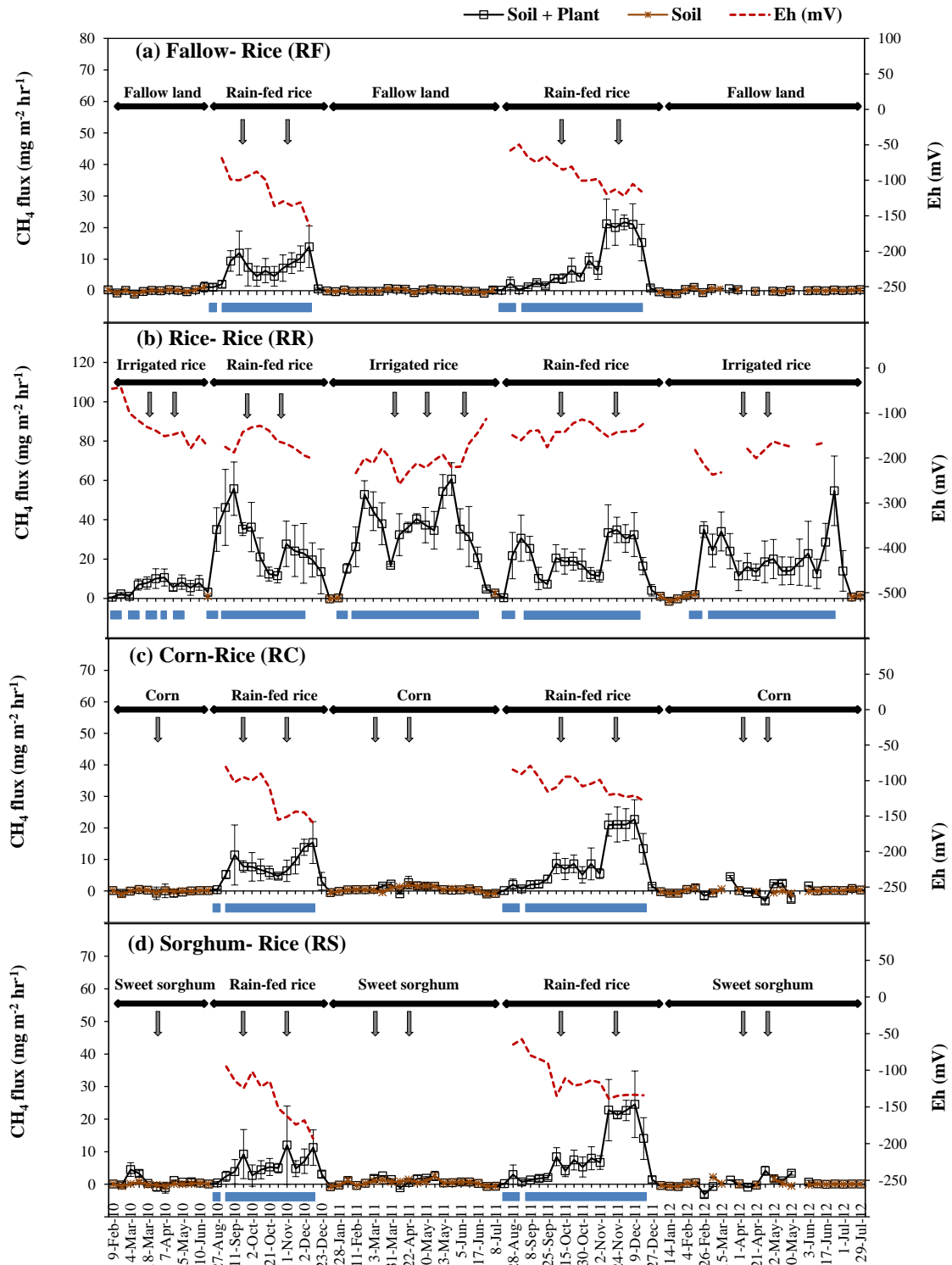


Figure 3.13 Seasonal variations of  $\text{CH}_4$  fluxes and soil redox potential (Eh)

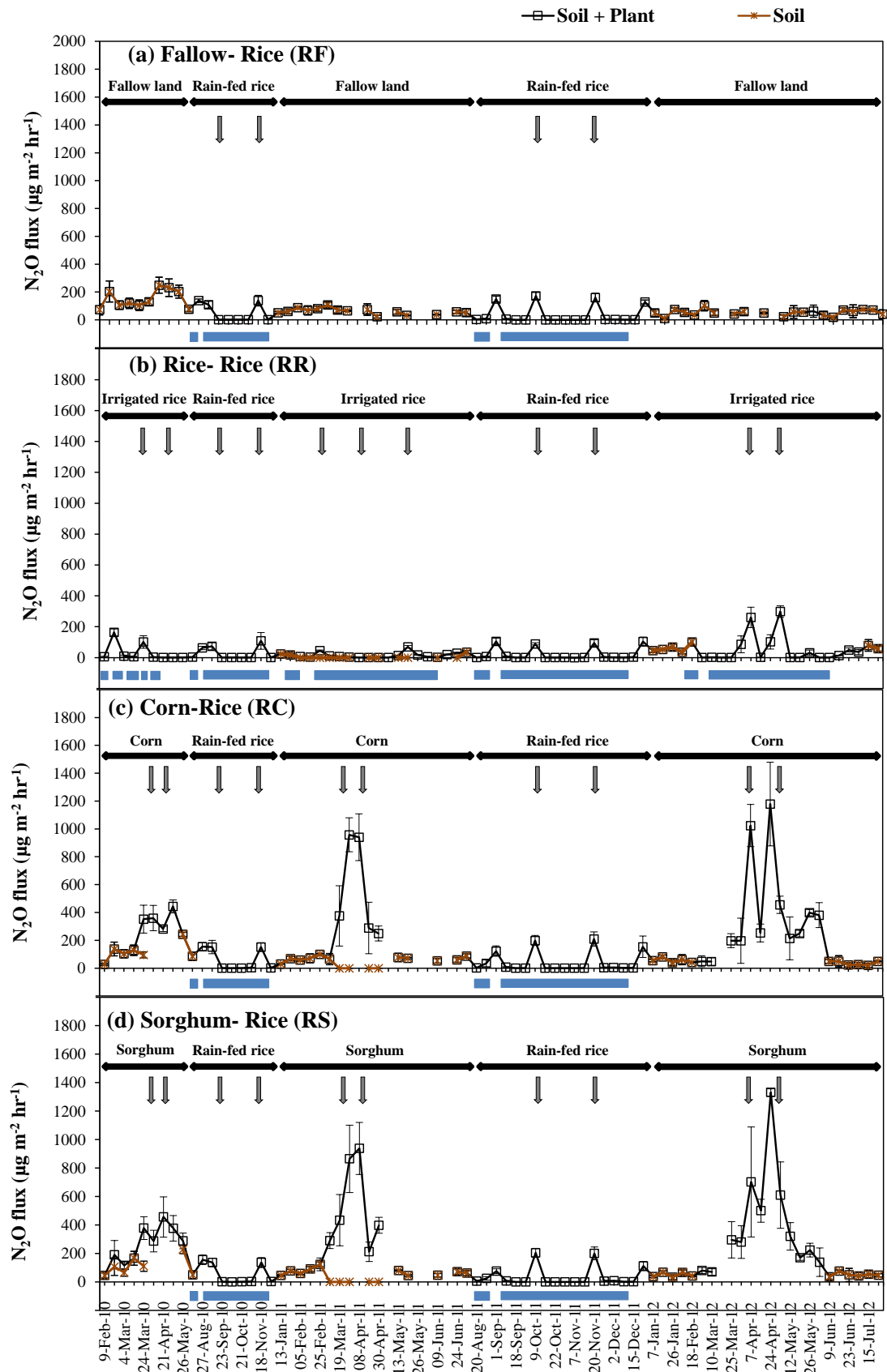
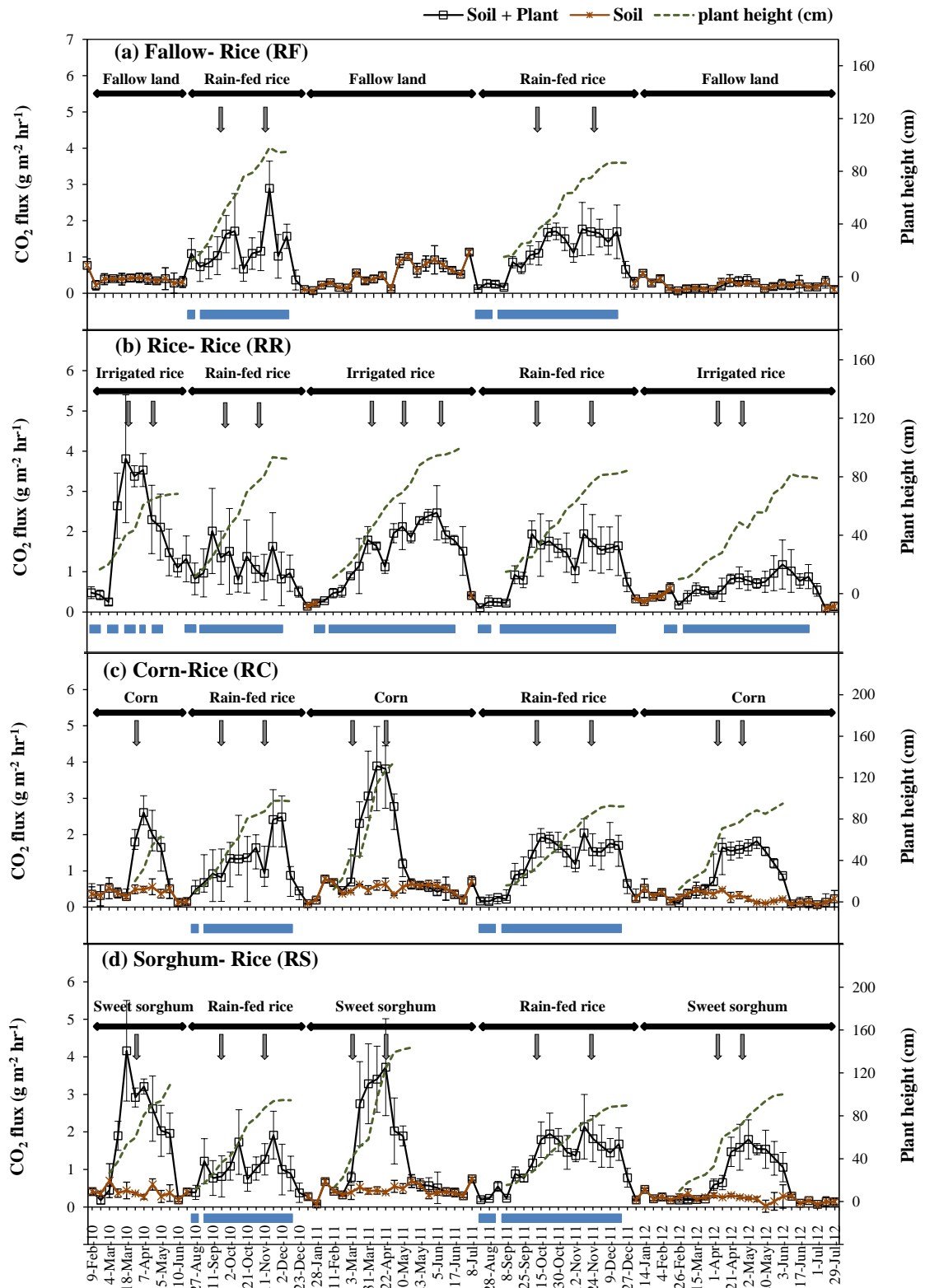


Figure 3.14 Seasonal variations of  $N_2O$  fluxes



**Figure 3.15** Seasonal variations of CO<sub>2</sub> fluxes and plant height

**Table 3.2** Seasonal accumulated emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>

Crop/Treatment	CH <sub>4</sub> (g CH <sub>4</sub> m <sup>-2</sup> crop <sup>-1</sup> )	N <sub>2</sub> O (mg N <sub>2</sub> O m <sup>-2</sup> crop <sup>-1</sup> )	CO <sub>2</sub> (kg CO <sub>2</sub> m <sup>-2</sup> crop <sup>-1</sup> )
1st crop in 2010			
RF (fallow)	-0.25±0.83 c	468.32±129.33 b	1.18±0.49 b
RC (Corn)	-0.50±1.84 c	646.04±93.01 ab	2.97±0.74 b
RR (Rice)	18.29±8.39 a	81.31±22.28 c	5.92±1.62 a
RS (Sorghum)	1.91±2.28 b	771.99±209.72 a	5.48±1.26 a
2nd crop in 2010			
RF (Rice)	18.84±9.93 b	108.40±24.39 a	3.14±1.34 a
RC (Rice)	20.39±8.85 b	130.63±32.24 a	3.41±1.67 a
RR (Rice)	71.05±25.49 a	72.28±27.69 a	3.06±1.70 a
RS (Rice)	14.66±9.79 b	120.76±28.82 a	2.73±1.24 a
3rd crop in 2011			
RF (fallow)	0.09±0.70 c	235.59±57.76 b	1.91±0.31 b
RC (Corn)	2.38±1.43 b	777.41±173.59 a	4.80±1.29 a
RR (Rice)	120.42±25.54 a	54.88±9.96 c	5.27±0.97 a
RS (Sorghum)	2.72±1.13 b	928.33±226.16 a	4.94±1.54 a
4th crop in 2011			
RF (Rice)	24.07±7.72 b	105.18±16.48 a	3.41±0.91 a
RC (Rice)	26.53±8.75 b	123.83±36.71 a	3.79±0.96 a
RR (Rice)	58.41±19.40 a	67.48±13.12 b	3.77±1.19 a
RS (Rice)	26.51±9.08 b	111.49±25.15 a	3.80±0.97 a
5th crop in 2012			
RF (fallow)	0.31±0.23 b	166.88±63.86 b	0.59±0.23 b
RC (Corn)	0.68±1.01 b	847.94±257.32 a	2.60±0.47 a
RR (Rice)	65.82±27.23 a	174.73±46.45 b	2.09±0.69 a
RS (Sorghum)	1.57±0.97 b	879.31±266.55 a	2.21±0.61 a

The values given are means ± standard deviations of six measurements.

Different letters denote significant differences ( $P < 0.05$ ) between seasonal crop rotation systems.

**Table 3.3** Annual accumulated emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>

Years	Treatments	Annual accumulated emissions		
		CH <sub>4</sub> (kg CH <sub>4</sub> ha <sup>-1</sup> y <sup>-1</sup> )	N <sub>2</sub> O (kg N <sub>2</sub> O ha <sup>-1</sup> y <sup>-1</sup> )	CO <sub>2</sub> (t CO <sub>2</sub> ha <sup>-1</sup> y <sup>-1</sup> )
2010	RF	185.84 ± 107.54 b	5.77 ± 1.54 a	43.26 ± 18.26 b
	RC	198.87 ± 104.25 b	7.77 ± 1.25 a	63.84 ± 24.18 ab
	RR	893.49 ± 338.84 a	1.54 ± 0.50 b	89.81 ± 33.18 a
	RS	165.72 ± 120.64 b	8.93 ± 2.39 a	82.12 ± 25.01 ab
2011	RF	241.62 ± 84.20 b	3.41 ± 0.74 b	53.20 ± 12.22 b
	RC	289.15 ± 101.84 b	9.01 ± 2.10 a	85.87 ± 22.47 a
	RR	1,788.26 ± 449.36 a	1.22 ± 0.23 c	90.45 ± 21.59 a
	RS	292.27 ± 102.14 b	10.40 ± 2.51 a	87.39 ± 25.12 a

The values given are means ± standard deviations.

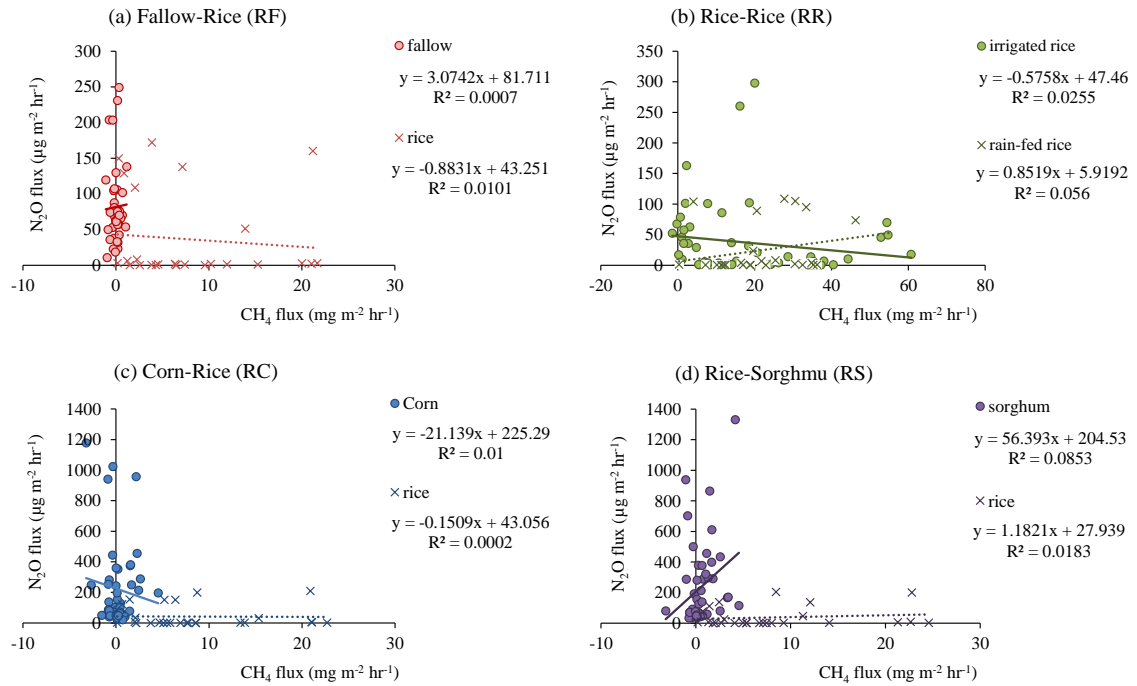
Different letters denote significant differences ( $P < 0.05$ ) between crop rotation systems in each year.

### 3.3.2 Interrelationships among emissions of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub>

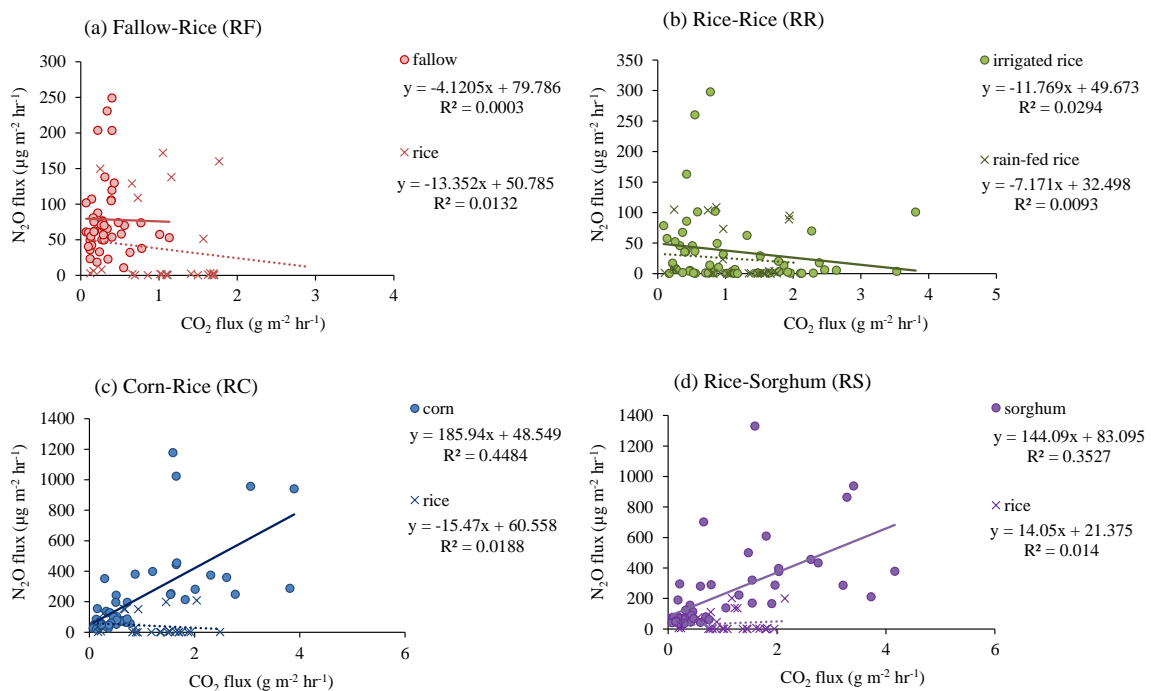
Obviously, CH<sub>4</sub> emissions were pronounced when the rice field was kept flooded (Figure 3.13), but N<sub>2</sub>O emissions were not pronounced (Figure 3.14). When the rice field was non-waterlogged and changed to energy crop cultivation, N<sub>2</sub>O emission occurred, while CH<sub>4</sub> emission rapidly decreased. During the rice growing season, the trends of CO<sub>2</sub> emission gradually increased from early stage (Figure 3.15) as same as the CH<sub>4</sub> emission. An interrelationships among their emissions were used to confirm these findings.

The relationship between the emissions of CH<sub>4</sub> and N<sub>2</sub>O (Figure 3.16) was not observed in all treatments. The trade-off relationship between their emissions was controlled by the water regime in the fallow land and growing season of energy crops and rice. The relationships between CO<sub>2</sub> (ecosystem respiration) and N<sub>2</sub>O emissions (Figure 3.17) were obviously found in the growing season of corn ( $R^2 = 0.4484$ ) and sweet sorghum ( $R^2 = 0.3527$ ), which were affected by fertilizer application under upland crop cultivation. An ecosystem respiration (CO<sub>2</sub>) was not correlated with CH<sub>4</sub> emissions (Figure 3.18) when all datasets over the fallow period and growing period of corn and sweet sorghum were plotted. During aerobic condition of fallow land and energy crop growing season, CO<sub>2</sub> emitted from

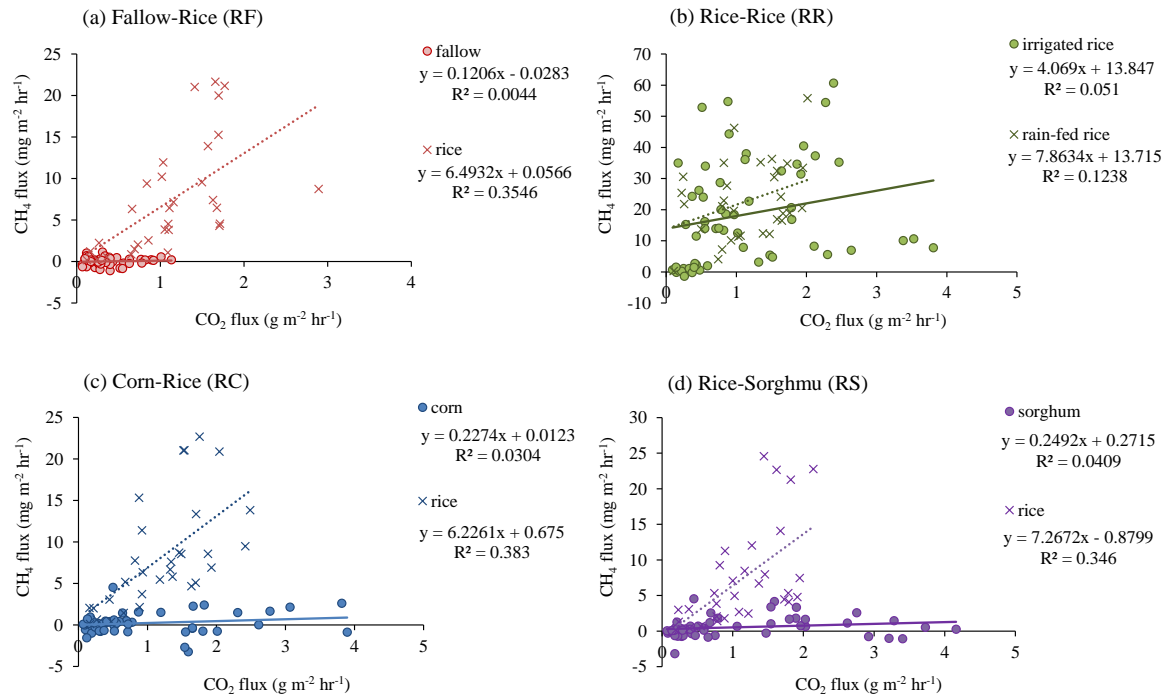
soil and plant, while  $\text{CH}_4$  were oxidized by methanotrophic bacteria. In the rice growing season of all treatments, relationships between these gases were found in the treatments of RF ( $R^2 = 0.3545$ ), RC ( $R^2 = 0.383$ ), and RS ( $R^2 = 0.346$ ), while RR was unpronounced.



**Figure 3.16** Relationship between  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions from four crop rotation systems



**Figure 3.17** Relationship between  $\text{CO}_2$  and  $\text{N}_2\text{O}$  emissions from four crop rotation systems

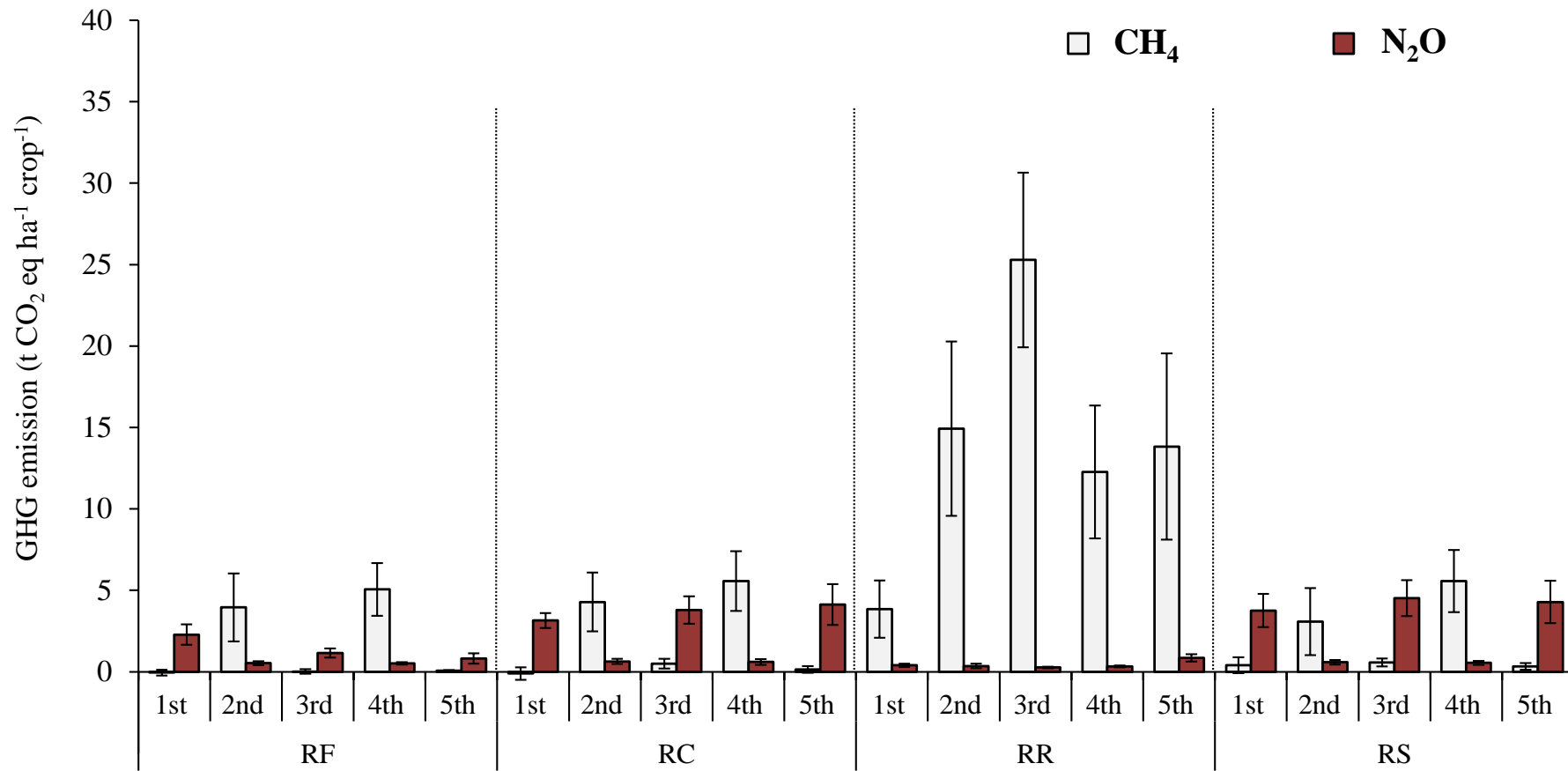


**Figure 3.18** Relationship between CO<sub>2</sub> and CH<sub>4</sub> emissions from four crop rotation systems

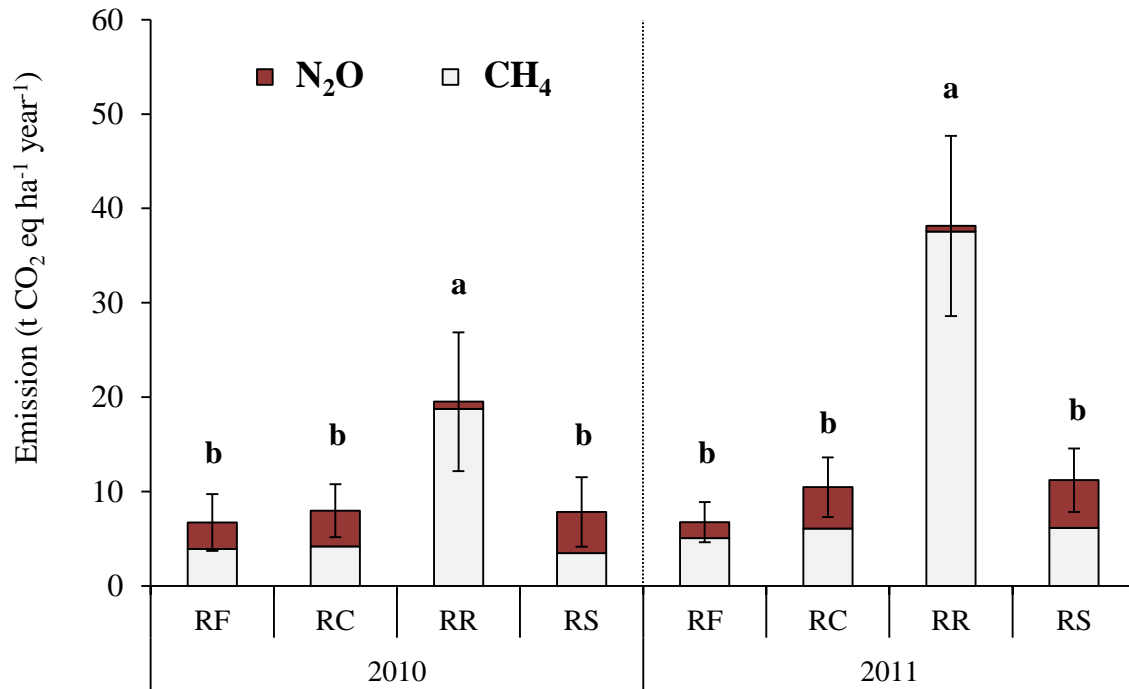
### 3.3.3 Seasonal and annual combined emissions of CH<sub>4</sub> and N<sub>2</sub>O

The seasonal combined emissions of CH<sub>4</sub> and N<sub>2</sub>O into CO<sub>2</sub> equivalents are presented in Figure 3.19. The N<sub>2</sub>O emissions into CO<sub>2</sub> equivalents were significantly observed in fallow period (RF) and energy crops (RC and RS) growing period in the dry seasons (1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> crop). CH<sub>4</sub> emissions were significantly observed in the rice cultivation, especially in RR treatment has obviously the large CH<sub>4</sub> emissions.

Although the energy crop rotations in rain-fed rice field leads to high N<sub>2</sub>O emissions, there are low total emissions into CO<sub>2</sub> equivalents when compared with CH<sub>4</sub> emission from rice cultivation (Figure 3.20). The combined emissions of CH<sub>4</sub> and N<sub>2</sub>O among two years (2010-2011) of crop rotation systems varies from 6.71 to 38.15 t CO<sub>2</sub> eq ha<sup>-1</sup> year<sup>-1</sup>. CH<sub>4</sub> emissions in double cropping of rice (RR) were significant higher than energy crop rotation (RC and RS) and fallow (RF) in the both year. The lowest of N<sub>2</sub>O emissions were found in RR treatment.



**Figure 3.19** Seasonal CO<sub>2</sub> equivalents of CH<sub>4</sub> and N<sub>2</sub>O emissions (mean  $\pm$  SD)



**Figure 3.20** Annual CO<sub>2</sub> equivalents of CH<sub>4</sub> and N<sub>2</sub>O emissions (mean ± SD)

### 3.3.4 Yield components of rice, corn and sweet sorghum, and their C and N contents

The crop yields components from the different crop rotation systems in 2010-2012 are given in Tables 3.4-3.6. The comparison of yield productions and database as shown in Table 3.7. The contents of carbon and nitrogen in their components as shown in Table 3.8

#### 3.3.4.1 Yield components of rice

In the rice cultivation, the yield components of the five crop seasons are shown in Table 3.4. The first crop of irrigated rice in 2010 was not growing well and very low crop yield because of rice seed cultivars and environmental effects. Under the rain-fed rice cultivation, the rice plant height, number of density and panicle, and dried straw and root were not significant different in both years 2010 and 2011. The rain-fed rice grain yields (outside chamber) in the rotation with corn (RC) and sweet sorghum (RS) were significant higher than single rice (RF) and double cropping of rice (RR), there varies from 2.79- 4.74 t ha<sup>-1</sup>. While, the rice grain yields that collected from inside-chamber were two times lower than outside-chamber.

#### **3.3.4.2 Yield components of corn**

The yield components in corn cultivation are presented in the dry season of the years 2010-2012 (Table 3.5). The first crop of corn in 2010 was not growing well, leading to low amounts of grain yield and dried crop biomass. After one year of corn rotation with rain-fed rice, the corn crop production in second year were increased grain yield by 1.35-1.38 t ha<sup>-1</sup>.

#### **3.3.4.3 Yield components of sweet sorghum**

The yield components of sweet sorghum are presented in the same season as the corn season (Table 3.6). The components of yield in the first year were also lower than the second and the third year. The amounts fresh sorghum stalk were 21.58 t ha<sup>-1</sup> in 2011 and 29.30 t ha<sup>-1</sup> in 2012. The extracted sorghum juice varies from 1.81 to 11.72 m<sup>3</sup> ha<sup>-1</sup>, with the rate of total soluble solids (sweetness) by 15-16 degree Brix.

#### **3.3.4.4 Comparison of yield productions**

The yield productions of irrigated and rain-fed rice from this research were found in the range with yield database from Office of Agricultural Economics (OAE) as presented in Table 3.7. It was found that the yield productions of corn and sweet sorghum were low quality and quantity.

#### **3.3.4.5 Carbon and nitrogen contents in crop yield components**

The percentages of carbon (C) and nitrogen (N) contents, and C/N ratios of crop production components listed in Table 3.8. In this study, crop productions were divided into aboveground (grains and straws (leaves + stems)) and belowground (roots). The high N content presented in root and straw of corn by 2.50% and 2.32%, respectively. Sweet sorghum found that high C content in grain, straw and root, there were 45.71%, 42.62% and 40.52% respectively. The C/N ratios were different among crops and their components, there were low in corn root (14) and corn straw (16).

**Table 3.4** Yield components of rice in five crop seasons

Crop/Treatment	Height (cm)	Density (stem m <sup>-2</sup> )	Panicle (panicle m <sup>-2</sup> )	Grain yield in- chamber (t ha <sup>-1</sup> )	Grain yield out-chamber (t ha <sup>-1</sup> )	Dried straw (straw+stubble) (t ha <sup>-1</sup> )	Dried root (t ha <sup>-1</sup> )
1st crop in 2010							
RR (Rice)	100.1±10.7	391±45	-	-	0.06±0.00	15.54±9.15	3.06±1.00
2nd crop in 2010							
RF (Rice)	93.4±3.2 a	509±108 a	307±55 a	2.08±1.02 a	4.31±0.31 a	6.56±1.26 a	5.67±1.47 a
RC (Rice)	97.9±2.4 a	443±68 a	335±37 a	2.62±1.23 a	4.72±0.46 a	8.23±1.46 a	4.31±1.56 a
RR (Rice)	90.9±4.3 a	483±85 a	343±33 a	2.44±0.60 a	4.60±0.31 a	6.28±1.50 a	5.73±1.29 a
RS (Rice)	95.8±8.0 a	472±92 a	324±31 a	1.64±0.47 a	4.70±0.48 a	7.94±1.80 a	5.42±3.91 a
3rd crop in 2011							
RR (Rice)	95.2±3.5	543±106	317±63	2.86±0.39	4.11±0.38	9.32±1.19	3.14±0.58
4th crop in 2011							
RF (Rice)	85.2±1.6 a	498±59 a	389±36 a	3.33±0.56 ab	3.84±0.26 b	4.78±1.28 a	4.10±1.23 a
RC (Rice)	89.8±4.6 a	513±58 a	426±72 a	3.95±0.77 a	4.74±0.10 a	5.09±0.59 a	5.60±2.14 a
RR (Rice)	80.4±2.9 a	537±78 a	404±62 a	2.60±0.32 b	2.79±0.26 c	5.46±0.64 a	4.54±1.24 a
RS (Rice)	85.7±5.2 a	565±66 a	409±43 a	3.69±0.97 a	4.73±0.48 a	5.43±1.94 a	6.02±1.30 a
5th crop in 2012							
RR (Rice)	97.7±2.3	574±85	509±65 b	3.63±1.16	4.35±0.30	6.41±1.33	7.29±0.82

The values are means ± SD ( $n=6$ ). Different letters denote significant differences ( $P < 0.05$ ) between crop rotation systems in each crop season.

**Table 3.5** Yield components of corn in three crop seasons

Crop/Treatment	Height (cm)	Density (stem m <sup>-2</sup> )	Grain yield (t ha <sup>-1</sup> )	Dried residue (t ha <sup>-1</sup> )	Dried root (t ha <sup>-1</sup> )
1st crop in 2010					
RC (corn)	62.8±2.7	4±0	0.03±0.00	0.09±0.05	0.01±0.00
3rd crop in 2011					
RC (Corn)	137.3±35.2	10±0	1.35±0.14	9.63±4.07	0.83±0.31
5th crop in 2012					
RC (Corn)	156.0±1.4	10±0	1.38±0.18	10.68±2.58	2.28±0.64

The values are means ± SD (*n*=6).

**Table 3.6** Yield components of sweet sorghum in three crop seasons

Crop/Treatment	Height (cm)	Density (stem m <sup>-2</sup> )	Grain yield (t ha <sup>-1</sup> )	Fresh stalk yield (t ha <sup>-1</sup> )	Juice (m <sup>3</sup> ha <sup>-1</sup> )	Sweetness (° Brix)	Dried residue (t ha <sup>-1</sup> )	Dried root (t ha <sup>-1</sup> )
1st crop in 2010								
RS (Sorghum)	100.0±20.3	20±5	0.20±0.05	4.53±1.95	1.81±0.78	15.0±0.0	1.51±0.00	1.00±0.00
3rd crop in 2011								
RS (Sorghum)	136.5±25.7	30±5	2.55±0.46	21.58±2.94	8.63±1.18	15.5±1.4	2.94±1.06	2.78±0.97
5th crop in 2012								
RS (Sorghum)	150.0±2.8	33±5	2.72±0.43	29.30±10.26	11.72±4.10	16.0±0.7	4.23±1.19	5.59±1.07

The values are means ± SD (*n*=6).

**Table 3.7** Comparison of yield production from yield databased and this study

Yield production	Yield database *	This study
Irrigated rice (t/ha)	3.98-4.24	4.11-4.35
Rain-fed rice (under irrigated area) (t/ha)	3.11-3.26	2.79-4.74
Corn (Maize) (t/ha)	4.06-4.23	1.35-1.38
Sweet sorghum (t/ha)	33.25-51.5	21.58-29.3
Sweetness of sorghum juice (° Brix), KU. 40	18-21	15-16

\* Source: The yield database were collected from OAE in year 2010-2012 (OAE, 2012).

**Table 3.8** Components of crop production and their C and N contents, and C/N ratios

Components	% C	% N	C/N
<b>Grain/seed</b>			
Rice	43.98	1.43	31
Corn	44.9	1.28	35
Sweet sorghum	45.71	1.81	25
<b>Straw</b>			
Rice	39.72	0.77	52
Corn	36.71	2.32	16
Sweet sorghum	42.62	1.45	29
<b>Root</b>			
Rice	29.4	0.98	30
Corn	35.76	2.5	14
Sweet sorghum	40.52	1.6	25

### 3.3.5 Greenhouse gas emissions on rice production

The ratio of greenhouse gas emissions per rice grain yield (Table 3.9) varies from 3.32-6.73 t CO<sub>2</sub>eq t<sup>-1</sup> yield for irrigated rice season and 0.75-4.45 t CO<sub>2</sub>eq t<sup>-1</sup> yield for rain-fed rice season. The highest emissions were observed in irrigated rice. One ton for rice production had significantly emitted high amounts of greenhouse gases.

**Table 3.9** Ratio of greenhouse gas emissions per rice yield in five crop rice seasons

Crop/Treatment	GHG emissions (t CO <sub>2</sub> eq ha <sup>-1</sup> y <sup>-1</sup> )	Rice yield (t ha <sup>-1</sup> )	GHGs / rice yield (t CO <sub>2</sub> eq/ t yield)
1st crop in 2010			
RF (fallow)	2.23±0.80 a	-	-
RC (Corn)	3.04±0.84 a	-	-
RR (Rice)	4.24±1.87 a	0.63±0.00	6.73±2.97
RS (Sorghum)	4.16±1.50 a	-	-
2nd crop in 2010			
RF (Rice)	4.48±2.20 b	4.31±0.31 a	1.02±0.44 b
RC (Rice)	4.92±1.96 b	4.72±0.46 a	1.01±0.32 b
RR (Rice)	15.27±5.49 a	4.60±0.31 a	3.28±0.97 a
RS (Rice)	3.67±2.20 b	4.70±0.48 a	0.75±0.39 b
3rd crop in 2011			
RF (fallow)	1.17±0.43 b	-	-
RC (Corn)	4.29±1.15 b	-	-
RR (Rice)	25.56±5.41 a	4.11±0.38	6.17±0.75
RS (Sorghum)	5.09±1.34 b	-	-
4th crop in 2011			
RF (Rice)	5.57±1.70 b	3.84±0.26 b	1.43±0.35 b
RC (Rice)	6.18±2.02 b	4.74±0.10 a	1.30±0.40 b
RR (Rice)	12.59±4.14 a	2.79±0.26 c	4.45±1.07 a
RS (Rice)	6.11±2.03 b	4.73±0.48 a	1.27±0.30 b
5th crop in 2012			
RF (Rice)	0.88±0.36 b	-	-
RC (Rice)	4.27±1.47 b	-	-
RR (Rice)	14.67±5.95 a	4.35±0.30	3.32±1.14
RS (Rice)	4.61±1.507 b	-	-

The values are means ± SD (n=6) with three sampling points in two replications of each treatments). Different letters denote significant differences ( $P < 0.05$ ) between crop rotation treatments in each crop season.

### 3.3.6 Economic estimation

The details of cost production rate at the field experiment in KMUTT, Ratchaburi are listed in Table 3.10. The economic estimation included costs of rice, corn and sweet sorghum crop production in each season, as shown in Table 3.11.

**Table 3.10** Rate of cost production in field experiment

No.	Cost item	Cost for crop production	Remark
1	Tillage wages by tractor	300 THB/rai	By local farmer's tractor
2	Labor wages	200 THB/person/day	cost in year 2010-2012
3	Chemical fertilizers		local costs at Ratchaburi
	- 15-15-15	650 THB/bag, or 13 THB/kg	application rate: - rice 25 kg/rai - corn 25 kg/rai - sweet sorghum 25 kg/rai
4	Chemical fertilizers		local costs at Ratchaburi
	- Urea (46-0-0)	800 THB/bag, or 16 THB/kg	application rate: - rice 20 kg/rai - corn 25 kg/rai - sweet sorghum 25 kg/rai
5	Seed costs		Seeding rate:
	- Rice	25 THB/kg	- rice 15 kg/rai
	- Corn	175 THB/kg	- corn 3 kg/rai
	- Sweet sorghum	40 THB/kg	- 1.5 kg/rai
6	Electricity costs for water management	4.5 THB/hour	Water pump: - VENZ VC-200, 2HP - pump rate: 30 m <sup>3</sup> /hour Water use: - rice 1,500 m <sup>3</sup> /rai - corn 900 m <sup>3</sup> /rai - sweet sorghum 800 m <sup>3</sup> /rai

**Table 3.11** Cost production of rice, corn and sweet sorghum in field experiments

<b>Crop</b>	<b>Cost items</b>	<b>Cost (THB/Rai)</b>	<b>Cost (THB/ha)</b>	
Rice	tillage wages (2 times)	600	3,750.00	
	planting wages (1 person/haft day)	100	625.00	
	harvest wages (4 persons/day)	800	5,000.00	
	fertilizer	645	4,031.25	
	seeds	375	2,343.75	
	electricity			
	- irrigated rice	225	1,406.25	
	- rain-fed rice	90	562.50	
	<b>Total</b>			
		<b>- irrigated rice</b>	<b>2,745.00</b>	<b>17,156</b>
	<b>- rain-fed rice</b>	<b>2,610.00</b>	<b>16,313</b>	
Corn	tillage wages (2 times)	600	3,750.00	
	planting wages (4 persons/day)	800	5,000.00	
	harvest wages (2 persons/day)	400	2,500.00	
	fertilizer	725	4,531.25	
	seeds	525	3,281.25	
	electricity	135	843.75	
	<b>Total</b>	<b>3,185.00</b>	<b>19,906</b>	
Sorghum	tillage wages (2 times)	600	3,750.00	
	planting wages (4 persons/day)	800	5,000.00	
	harvest wages (2 persons/day)	400	2,500.00	
	fertilizer	725	4,531.25	
	seeds	60	375.00	
	electricity	120	750.00	
	<b>Total</b>	<b>2,705.00</b>	<b>16,906</b>	

As shown in Table 3.11, the cost productions of rice, corn and sweet sorghum in the field experiment were higher 2-4 times when compared with cost based data as listed in Table 3.12. The costs in this study were high in labor wage for crop planting and harvest (30-40% of total cost), while the most of local farmer used the machine which was lower cost.

**Table 3.12** Comparison of costs of production from cost database and this research

Cost production	Cost database * (THB/ha)	This research (THB/ha)
1. Irrigated rice	10,148	17,156
2. Rain-fed rice	8,207	16,313
3. Corn (Maize)	5,955	19,906
4. Sweet sorghum	7,850	16,906

\* Source: The cost database were collected from OAE in years 2010-2012 (OAE, 2012).

The amounts of crop productions, crop production price and crop yield income in 2010-2012 (Tables 3.13-3.15) were used for economic estimation. The first crop of rice, corn and sweet sorghum that started in dry season 2010 was very low crop yield, there were lost money 13,000-20,000 THB ha<sup>-1</sup>. Due to the corn yield productions in year 2010-2012 were still lower than yield database (OAE, 2012), while the cost productions still high, and there were lost money 8,500-20,000 THB ha<sup>-1</sup>.

However, the possible income was estimated in only year 2011, there is the good crop yield production than year 2010. The double crop cultivation for each year, the farmer will get more possible income 43,699 THB or 1,434 USD ha<sup>-1</sup> year<sup>-1</sup> for sweet sorghum-rice, 28,964 THB or 950 USD ha<sup>-1</sup> year<sup>-1</sup> for rice-rice and 22,904 THB or 751 USD ha<sup>-1</sup> year<sup>-1</sup> for corn-rice rotation systems. Although, if the farmers cultivate only rain-fed rice, they will lose opportunity for possible incomes as 20-47%. Moreover, the increasing of crop production can make more money, especially in corn cultivation.

**Table 3.13** Amounts of crop production, crop product prices and possible crop yield incomes in 2010

Treatments	Yield	Irrigated rice and energy crops in 2010				Rain-fed rice crop in 2010				Total Income (THB/ha/year)	Total Income (USD/ha/year) **
		cost production (THB/ha)	Yield (kg/ha)	Price* (THB/ kg)	net Income THB/ha	cost production (THB/ha)	Yield (kg/ha)	Price* (THB/ kg)	net Income THB/ha		
RF	- Grain rice	-	-	-	-	16,313	4,313	8.6	20,779	20,779	653
RC	- Grain corn	19,906	31	8.1	-19,655	-	-	-	-	4,616	145
	- Grain rice	-	-	-	-	16,313	4,719	8.6	24,271		
RR	- Grain rice	17,156	63	7.7	-16,671	16,313	4,603	8.6	23,273	6,602	208
RS	- Grain sorghum	16,906	201	5.8	-13,024	-	-	-	-	11,118	350
	- Stalk sorghum		4,527	0.6		-	-	-			
	- Grain rice	-	-	-	-	16,313	4,704	8.6	24,142		

\* Prices of yield production data were taken from Office of Agricultural Economics (2010, 2011)

\*\* Exchange rate average in 2010= 31.80 THB/USD, 2011= 30.48 THB/USD, 2012 = 30.98 THB/USD)

(Source: <http://www.x-rates.com/average/?from=USD&to=THB&amount=1&year=2012>)

**Table 3.14** Amounts of crop production, crop product prices and possible crop yield incomes in 2011

Treatments	Yield	Irrigated rice and energy crops in 2011				Rain-fed rice crop in 2011				Total Income (THB/ha/year)	Total Income (USD/ha/year) **
		Cost production (THB/ha)	Yield (kg/ha)	Price* (THB/ kg)	net Income THB/ha	cost production (THB/ha)	Yield (kg/ha)	Price* (THB/ kg)	net Income THB/ha		
RF	- Grain rice	-	-	-	-	16,313	3,837	10.3	23,209	23,209	761
RC	- Grain corn	19,906	1,354	7.6	-9,616	-	-	-	-	22,904	751
	- Grain rice	-	-	-	-	16,313	4,741	10.3	32,520		
RR	- Grain rice	17,156	4,113	8.2	16,570	16,313	2,787	10.3	12,394	28,964	950
RS	- Grain sorghum	16,906	2,550	6	11,344	-	-	-	-	43,699	1,434
	- Stalk sorghum		21,583	0.6		-	-	-	-		
	- Grain rice	-	-	-	-	16,313	4,725	10.3	32,355		

\* Prices of yield production data were taken from Office of Agricultural Economics (2010, 2011)

\*\* Exchange rate average in 2010= 31.80 THB/USD, 2011= 30.48 THB/USD, 2012 = 30.98 THB/USD)

(Source: <http://www.x-rates.com/average/?from=USD&to=THB&amount=1&year=2012>)

**Table 3.15** Amounts of crop production, crop product prices and possible crop yield incomes in 2012

Treatments	Yield	Irrigated rice and energy crops in 2012				Total Income (USD/ha/crop) **
		Cost production (THB/ha)	Yield (kg/ha)	Price* (THB/kg)	net Income THB/ha	
RF	- Grain rice	-	-	-	-	-
RC	- Grain corn	19,906	1,375	8.3	-8494	-274.17
	- Grain rice	-	-	-	-	
RR	- Grain rice	17,156	4,350	10.3	27649	892
RS	- Grain sorghum	16,906	2,717	6.7	21806	704
	- Stalk sorghum		29,298	0.7		
	- Grain rice	-	-	-	-	

\* Prices of yield production data were taken from Office of Agricultural Economics (2010, 2011)

\*\* Exchange rate average in 2010= 31.80 THB/USD, 2011= 30.48 THB/USD, 2012 = 30.98 THB/USD)

(Source: <http://www.x-rates.com/average/?from=USD&to=THB&amount=1&year=2012>)

### 3.4 Discussion

The different of four crop rotation systems in the field experiment was influence to CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> (ecosystem respiration) emission and crop yields. Their effects are discussed below.

#### 3.4.1 Effect of energy crop rotation on CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> emissions

##### 3.4.1.1 CH<sub>4</sub> emission

The seasonal variations of CH<sub>4</sub> fluxes were significantly observed during the rice cultivation period in all treatments (Figure 3.13). The CH<sub>4</sub> fluxes gradually increased during the continuously flooded period with the soil redox potential (Eh) decreased and CH<sub>4</sub> fluxes rapidly decreased after field drainage. In all treatments, the lower soil Eh was found at the early state and flowering state of rice cultivation resulted in higher CH<sub>4</sub> fluxes. This is a well understood pattern of CH<sub>4</sub> emission in anaerobic conditions as indicated by the changes in redox potential (Eh) values (Yagi and Minami, 1990; Yang and Chang 1998; Siriratpiriya and Pradubsuk, 2002; Minamikawa and Sakai, 2007). The change in soil Eh is controlled by the various oxidized components (O<sub>2</sub>, NO<sub>3</sub><sup>-</sup>, Mn<sup>4+</sup>, SO<sub>4</sub><sup>2-</sup>, Fe<sup>3+</sup> and CO<sub>2</sub>) under flooded condition (Sahrawat, 2004).

The highest CH<sub>4</sub> flux was found in the RR treatment, which is consistent with the lowest soil Eh (-100 to -250 mV), especially in the 2<sup>nd</sup> and 3<sup>rd</sup> crop. This results can be explained by the incorporation of organic matter and crop residues, duration and condition of decomposition, and water management in rice field. Namely, the incorporation 10 ton ha<sup>-1</sup> of cow manure and 10.4 ton ha<sup>-1</sup> of rice residue (Table 3.1) before the 2<sup>nd</sup> crop and their decomposition under anaerobic condition of flooded soil resulted in higher CH<sub>4</sub> emission in the 2<sup>nd</sup> crop. Moreover, the large emission from the 3<sup>rd</sup> crop was also observed. Due to the short duration (7 days) for the rice residues (9.9 ton ha<sup>-1</sup>) decomposition during the interval period of field preparation before rice cultivation, resulting in an abundant organic matter used for CH<sub>4</sub> fermentation. In the 2<sup>nd</sup> to 5<sup>th</sup> crops of RR, significance amounts of rice residue were applied to the field (Table 3.1), and high CH<sub>4</sub> emissions were observed accordingly. Fores *et al.*, (1998) found that incorporated rice straw in a rice field during the dry season decomposed at a rate of 0.0075 day<sup>-1</sup>, and after 139 days of decomposition was remained 75% of the biomass, 70 % of the carbon and 50 % of the nitrogen. Therefore, a time limit on decomposition and slow decomposition rate of rice residue resulted in the large amount of carbon left in the soil in our experiment caused high CH<sub>4</sub> emission during the rice growing

period. While, the smaller CH<sub>4</sub> emission was found in the first crop because no rice residues were incorporation and less water was used for cultivation during the dry season.

During the rain-fed rice seasons (2<sup>nd</sup> and 4<sup>th</sup> crops), CH<sub>4</sub> emissions were also observed in the treatments of RF, RC and RS, and accumulated emission were not significant different (Table 3.2). In the 4<sup>th</sup> crop, although the different types and amounts of crop residues (rice, corn and sweet sorghum) were applied (Table 3.1), CH<sub>4</sub> emissions from the rain-fed rice which rotated with corn (RC) and sweet sorghum (RS) were similar and their emissions were lower than that continuous rice (RR) (Figure 3.13, Table 3.2). This result can be explained by the different C/N ratios and the timing of the residue incorporations. Due to their relatively low C/N ratios (Table 3.8), residues of corn and sweet sorghum in RC and RS treatments, respectively were probably rapidly decomposed (Sahrawat, 2003) than rice residue in RR treatment under aerobic condition during the fallow period in RF plot and field preparation in RC and RS plots before rain-fed rice cultivation. Thus, only less substrates in the following rain-fed rice cultivation season were available and 54-71% lesser CH<sub>4</sub> emission as a result.

The seasonal accumulated CH<sub>4</sub> emissions from the rain-fed rice in all treatments varies from 14.66 to 71.05 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup> (or 1.22-5.92 kg CH<sub>4</sub> ha<sup>-1</sup> d<sup>-1</sup>) in 2010 and 24.07 to 58.41 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup> (or 1.87-4.53 kg CH<sub>4</sub> ha<sup>-1</sup> d<sup>-1</sup>) in 2011. There are in agreement with other studies in Thailand, including Bang Khen (55.20 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>) (Katoh *et al.*, 1999a), Sun Pa Thong (39.80 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>) (Katoh *et al.*, 1999b), Surin (39.30 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>) (Katoh *et al.*, 1999c), and Samut Sakorn (24.36 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>) (Towprayoon *et al.*, 2005). The accumulated CH<sub>4</sub> emission from rain-fed rice with energy crop rotation and fallow land (14.66-26.53 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>) were significantly lower than those with irrigated rice (RR) rotation (58.41-71.05 g CH<sub>4</sub> m<sup>-2</sup> crop<sup>-1</sup>). Similar results were reported by Adhya *et al.*, (2000) they found that CH<sub>4</sub> emissions from the rotation of upland crop-rice (12.52–13.09 g CH<sub>4</sub> m<sup>2</sup> crop<sup>-1</sup>) was lower than the rotation of rice-rice (39.96 g CH<sub>4</sub> m<sup>2</sup> crop<sup>-1</sup>).

The annual emissions of CH<sub>4</sub> (two crops combined, Table 3.3) confirm that crop rotation other than rice in the dry season reduced annual CH<sub>4</sub> emissions. The results also show that the CH<sub>4</sub> emission in 2010 were less than those in 2011 because the first crop in 2010 was on an abandoned rice field and water shortage. The selected energy crops (corn and sorghum) rotation with rain-fed rice reduced CH<sub>4</sub> emission by 55-79% in rice-fed season and reduced by 78-84% of annual emission when compared with continuous rice.

### 3.4.1.2 N<sub>2</sub>O emission

N<sub>2</sub>O fluxes were significantly observed in the fallow period and corn and sweet sorghum growing season, and increased after fertilizer application (Figure 3.14). The large N<sub>2</sub>O peaks appeared after fertilizer was added due to increasing N availability, which peaks were mainly attributed to nitrification under aerobic condition (Hou and Tsuruta, 2003). In rain-fed rice season, the patterns of seasonal variations of N<sub>2</sub>O fluxes similar to that of CH<sub>4</sub> fluxes were observed in all treatments (Figure 3.14). N<sub>2</sub>O fluxes were increased after drainage and fertilization events. This can be explained by the fact that draining changes conditions from anaerobic to aerobic, and this promotes N<sub>2</sub>O production as an intermediate product of nitrification and denitrification (Zheng *et al.* 2000). Similar effects of drainage have been found by Towprayoon *et al.*, (2005). The application of chemical fertilizer significantly emitted the N<sub>2</sub>O emissions, which were found in all rice seasons. Abao *et al.* (2000) found that the adding fertilizer increased the availability of substrate for nitrification and denitrification.

According to fertilizer application in the different crop conditions, N<sub>2</sub>O fluxes in rice seasons were significantly lower than that in corn and sweet sorghum season (Figure 3.14). Due to N from fertilizer can be lost from flooded rice field through ammonia volatilization (Freney *et al.*, 1981; Freney *et al.*, 1990). Freney *et al.* (1981) found that ammonia was lost from the fertilizer applied by 5.1 % at the pre-planting and 10.6% at the panicle initiation stage. Zhang *et al.* (2013) also found that N losses during the rice seasons were higher than those during the wheat seasons and were related to rainfall.

In the same field condition during rain-fed rice season, the incorporation of rice, corn and sweet sorghum residues in RR, RC and RS treatment, respectively did not affect the patterns of N<sub>2</sub>O fluxes (Figure 3.14), even though their residue amounts were different (Table 3.1). These fluxes have the same pattern emissions as in RF treatment. The amounts of seasonal accumulated N<sub>2</sub>O emissions from rain-fed rice season (2<sup>nd</sup> and 4<sup>th</sup> crop) were not different among the treatments, except RR treatment in the 4<sup>th</sup> crop (Table 3.2). This result indicated that continuous rice residue incorporation in RR treatment influenced on N<sub>2</sub>O reduction after two-year rotations. Previous studies found that crop residues with a higher C/N ratios give low N<sub>2</sub>O emissions and vice versa (Millar *et al.*, 2004; Toma and Hatano, 2007; Yao *et al.*, 2010; Yao *et al.*, 2013). Yao *et al.* (2013) pointed that the incorporation of wheat straw with high C/N ratio by 146 before rice transplanting had a residual inhibitory effect on N<sub>2</sub>O emission, consistently resulting in 40% lower emission

compared to the treatment without wheat straw incorporation. Likewise, in this experiment, the higher C/N ratio in rice straw (52, see Table 3.8) in RR is considered to have decomposed slower than that the residue of corn (16) and sweet sorghum (29) under the flooded rice condition. This consequently influenced to low N substrate availability for N<sub>2</sub>O production in RR treatment.

The energy crop rotations of RC and RS produced higher annual emissions of N<sub>2</sub>O than that the RF and RR treatments (Table 3.3). These results are in agreement with those found by Yao *et al.*, (2010) with rice-wheat rotation in Suzhou in China. The significant different N<sub>2</sub>O fluxes between the rice growing seasons and energy crop seasons were depended on the different crop condition, nitrogen fertilizer application, non-flooding period in rice field, and crop residue incorporation. Whenever, the land use changed from the flooded rice condition to upland crops (either corn or sorghum) N<sub>2</sub>O was significantly observed. Therefore, the rotation of rice field by energy crop should be avoided emission of N<sub>2</sub>O.

#### **3.4.1.3 CO<sub>2</sub> emission (ecosystem respiration)**

The seasonal variations of CO<sub>2</sub> fluxes (Figure 3.15) were measured the soil heterotrophic respiration and the ecosystem respiration (plant and soil heterotrophic), there had similar patterns in the four crop rotation treatments but only slightly dissimilar seasonal accumulated emission (Table 3.2). In the RC and RS cases, the corn and sorghum plants grew too high towards the end of the growing period, and had to be cut above ground so that the gas sampling chamber (which were limited in height) could be used. This resulted in declines in the CO<sub>2</sub> fluxes measured in these cases. Apart from this technical problem, the seasonal trends of CO<sub>2</sub> fluxes observed were consistent with the patterns and trends of plant growth.

In all plant crops, the CO<sub>2</sub> fluxes had also increased after nitrogen fertilizer application. N-fertilizer improved crop growth through increases leaf thickness and consequently their photosynthesis and respiration (Holou, 2010). The added chemical fertilizer formulas, 15-15-15 and 46-0-0 (Table 3.1), which are considered appropriate for energy crop growth and increased ecosystem respiration (Figure 3.17). The most of the CO<sub>2</sub> emitted by fallow land is from soil respiration via the decomposition process of rice residue. In crop growing season, CO<sub>2</sub> was emitted from the respiration of plants and soil microorganisms (ecosystem respiration). During the corn and sweet sorghum crop season, the CO<sub>2</sub> emission from the soil was 8-31% when compared with total ecosystem respiration

(see Chapter 4, Table 4.3 in the “Oc” term). In rain-fed rice season, the accumulated CO<sub>2</sub> emission (ecosystem respiration) was 2.73-3.41 kg CO<sub>2</sub> m<sup>-2</sup> crop<sup>-1</sup> in the 2<sup>nd</sup> crop and 2.60-3.95 kg CO<sub>2</sub> m<sup>-2</sup> crop<sup>-1</sup> in the 4<sup>th</sup> crop, their emissions were not significantly different in all treatments (Table 3.3). After rain-fed rice harvest, amounts of crop biomass are considered in the same among the four treatments (Table 3.4).

### **3.4.2 Effect of energy crop rotation on greenhouse gas emissions and rice crop production**

In the 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> of corn (RC) and sweet sorghum (RS) season, CO<sub>2</sub> equivalent from N<sub>2</sub>O emissions were higher than those emissions, due to an intermediate product of nitrification and denitrification under aerobic conditions (Figure 3.19). Anyhow, this result also found in fallow period (RF). The rice cultivation obviously effected on CO<sub>2</sub> equivalent from CH<sub>4</sub> emission in all rice seasons and treatments. The related results were also found in the study of Nishimura *et al.*, (2011).

The combined annual CO<sub>2</sub> equivalent emissions varied from 6.71 to 38.15 t CO<sub>2</sub>eq ha<sup>-1</sup> year<sup>-1</sup> (Figure 3.20). Highest annual CO<sub>2</sub> equivalent emissions were significant observed in RR treatment in both years (2010 and 2011), there have to be continue incorporation and decomposition of rice residue, leading to a lot of substrate for CH<sub>4</sub> production. This result indicated that the crop management system by continuous rice able to continue increasing in CH<sub>4</sub> emission. While, annual CO<sub>2</sub> equivalents in RC and RS treatments were lower than that in RR and their emissions were not significant different in both years. Moreover, the treatments of RC and RS were similar amount CO<sub>2</sub> equivalent emissions from N<sub>2</sub>O and CH<sub>4</sub> emission. Because these results are combined amount of N<sub>2</sub>O and CH<sub>4</sub> emission in each year, which their emissions have available in large quantities of N<sub>2</sub>O emission from energy crop season and CH<sub>4</sub> emission from rain-rice season. For the local practice treatment, namely RF, CO<sub>2</sub> equivalent emissions were not significant different with RC and RS treatments in both years. These results indicated that the rotation with corn (RC) and sweet sorghum (RS) able to reduced equivalent CO<sub>2</sub> emission by 59-73 % when compared with double cropping of rice (RR).

For the first crop in the dry season of 2010, the yields of all the crops were low, (Table 3.4) because even though the fields had been well prepared in advance, there was limited water supply to the field and the high air temperature at the beginning of crop cultivation (Figure 3.2), leading to plants grow poorly. In the second crop of 2010 the grain yields of the rain-fed rice were good and not significantly different in the four crop rotation

treatments. In the third crop (2011) the yields of the energy crops in RC and RS increased, and the yield of the irrigated rice in RR was much greater than that in 2010. These increased yields may be due to the rain coming early, the better water supply to the field, added urea by two times, and also improvements in the soil organic matter and nutrients (Zeng *et al.*, 2007). In the fourth crop (2011), the rain-fed rice yields in RC and RS were maintained, but in RF the yield fell slightly, and in RR the yield was reduced 39%, due to the low soil quality that results from continuous monocropping of rice under flooded soil conditions (Cassman and Pingali, 1995). Similar effects of continuous rice cropping were found by Achim *et al.* (2000). In the fifth crop (2012), the yield of the irrigated rice in RR was not different with the third crop in 2011.

Talking in to GHG emissions in the rice production (Table 3.9), the ratios varied 3.32-6.73 t CO<sub>2</sub>eq per ton of rice yield for irrigated rice season and 0.75-4.45 t CO<sub>2</sub>eq per ton of rice yield for rain-fed rice season. The large ratios of emissions were observed in irrigated rice season in years 2010-2012. In rain-fed rice seasons, the RC and RS rotations were lower emission (0.75-1.3 t CO<sub>2</sub>eq per ton of rice yield), while continuous rice (RR) was highest emission (3.28-4.45 t CO<sub>2</sub>eq per ton of rice yield) in both years 2010 and 2011.

The experimental results showed that the rotation of rain-fed rice with corn and sweet sorghum were provided less combined GWP by the CH<sub>4</sub> and N<sub>2</sub>O emissions compared to that of the irrigated rice but also improved rice yield production. Moreover, the results also suggest that the increasing of rice production is able to reduce the ratio of greenhouse gas emission, especially in RC and RS treatments.

### 3.5 Summary and Conclusion

The utilization of fallow period in rain-fed rice field by selected energy crop rotations (RC and RS) reduced 78-84% of CH<sub>4</sub> compared to continuous rice (RR). In terms of annual CO<sub>2</sub> equivalent emissions, RR had the highest emissions in the form of CH<sub>4</sub>, while the single cropping of rice (RF) and RC and RS reduced emissions over 50%. Furthermore, annual CO<sub>2</sub> equivalent emissions in rotated treatments does not seem to have any difference on CH<sub>4</sub> and N<sub>2</sub>O emissions.

The rain-fed rice grain yields in the rotation with corn (RC) and sweet sorghum (RS) were significantly higher than the single rice (RF) and double cropping of rice (RR), which varied from 2.79 to 4.74 t ha<sup>-1</sup>. This result indicated that the rotation of energy crop (both

corn and sweet sorghum) was significant improved rain-fed rice yield after consecutively cultivation, which is required to feed population, and also decreased the ratio of GHG emission per rice grain yield.

In order to expect economic and social benefits, it is suggested that if farmers cultivate double crops of sweet sorghum+rice, rice+rice and corn+rice rotation for each year, they will earn more possible income 43,699-22,904 THB or 1,434-751 USD ha<sup>-1</sup> year<sup>-1</sup>. While, if farmers will cultivated only rain-fed rice (RF), they will lost opportunity for possible incomes as 20-47%. Moreover, the increasing of crop production and reducing of cost production can make more money for farmer. Finally, this crop rotation management has been the suitable cropping option for greenhouse gas mitigation and rice production.

The implementation of energy crop rotation management in rain-fed rice field is the one choice which not only reduced GHG emissions, but also increased farmer income by increased crop yields, saving water in the crop cultivation, and enhanced agricultural land use. However, the problems of water supply, soil quality, climate, crop marketing and competition between food and energy crops are the limitation for this management system.

**CHAPTER 4**  
**SOIL CARBON DYNAMIC IN THE ENERGY CROP ROTATIONS**  
**IN RICE FIELD**

**4.1 Introduction**

The areas of global rice productions were approximately 165 million ha, and about 52 million ha devoted to rain-fed lowlands rice. Rice is produced and consumed in Asia cover about 147 million ha or almost 90% of the world rice harvested area (FAOSTAT, 2013; GRiSP, 2013). In Thailand, the rice cultivation is very important, which covers almost 50% of the country's arable land (OAE, 2008:2010). An approximately 60% of rice cultivation area is normally to grow a single rain-fed rice crop each year (~four months) and then being left as the fallow land about eight months in the dry season (OAE, 2008, 2012). This cropping system is conventional practice which its poor management during fallow period, loss in soil fertility and nutrition occurred. Many rain-fed rice areas in Thailand have low soil fertility (Jongdee *et al.*, 1997) and over 2000,000 ha have been abandoned (LDD, 2010). These areas are not well managed for agricultural purposes due to its poor soil properties and water shortage, leading to low rice yield.

In order to improve utilization of agricultural land and soil quality, many references reported that the use of suitable cropping systems and plant residue management methods can improve soil organic carbon (SOC) sequestration. These can reduce carbon loss to the atmosphere, lead to better soil fertility and improve crop productivity (Li and Feng, 2002; Qiu *et al.*, 2005; Tang *et al.*, 2006; Dawson and Smith, 2007; Al-Kaisi, 2008; Nishimura *et al.*, 2008; Kukal *et al.*, 2009; Singh *et al.*, 2009; Ali *et al.*, 2012). The supplied carbon to the soil in form of returned crop residue influenced on soil carbon budget (SCB) (Sahrawat, 2003).

The rotations of upland crop cultivations in rice fields have been increased agricultural land utilization. There have affected the nutrient imbalance in the plant and soil (Deog-Bae *et al.*, 2005) and also improved soil fertility, soil organic carbon (SOC) content, and sustainable crop productivity (Zeng *et al.*, 2007; Kukal *et al.*, 2009; Ali *et al.*, 2012). Rice-upland rotation fields are unique from other wetland or upland soils, because they are associated with frequent cycling between wetting and drying under anaerobic and aerobic conditions (Zhou *et al.*, 2014). During rice season, the number and activity of anaerobic

microbe are increasing, which not only leads to the slower decomposition of organic matter and contributes to SOM accumulation but also promotes the production of toxic substances, such as CH<sub>4</sub> (Ponnamperuma, 1972). During the upland crop season, the biological N fixation is reduced and SOM mineralization is facilitated, therefore accelerating SOM loss (Witt *et al.*, 2000).

Now, the crop rotation in fallow period after the rain-fed rice is not appropriate due to soil quality and limitation of water. This study introduced corn and sweet sorghum as the rotation crop in the rain-fed rice field due to their have short growing period crops (~ 4 months), low water demand, and drought resistance. Therefore, this study aim to verify the effects of the crop rotations in rice field on soil properties, soil carbon budget and soil organic carbon stock. The understanding of their soil characteristics is necessary for the sustainable development of the agricultural land and contribute to the improvement of soil quality and crop yield.

## **4.2 Methodology**

### **4.2.1 Soil sampling and analysis**

Three soil samples were collected from the site experiment (see Chapter 3) in each of the eight field plots at soil depths of 0-15 cm and 15-30 cm after each crop harvest (Figure 4.1 (a)). The samples were air dried, ground by hand, and passed through a 2 mm sieve. The soil samples were analyzed for texture by hydrometer method, pH by 1:1 of soil:water method, organic matter (OM) by wet oxidation method (Walkley and Black, 1934), nitrogen by Kjeldahl method, phosphorus by Bray II method and determined by spectrophotometer, and potassium by ammonium acetate extraction method, and determined by atomic absorption spectrophotometer.

The soil bulk density was measured at three different random places in each field plot at soil depths of 0-15 cm and 15-30 cm after each crop harvest using stainless steel cylinders of 5.0 cm internal diameter and 5.0 cm height also collected after the harvest (Figure 4.1(b)). The soil cores were dried in an oven at 105 °C for 48 hours. The ratio of the dry weight of the soil core and the internal volume of the stainless steel cylinder gave the bulk density.



(a) soil sampling at depth of 0-15 cm and 15-30 cm



(b) soil bulk density measurement by stainless steel cylinders

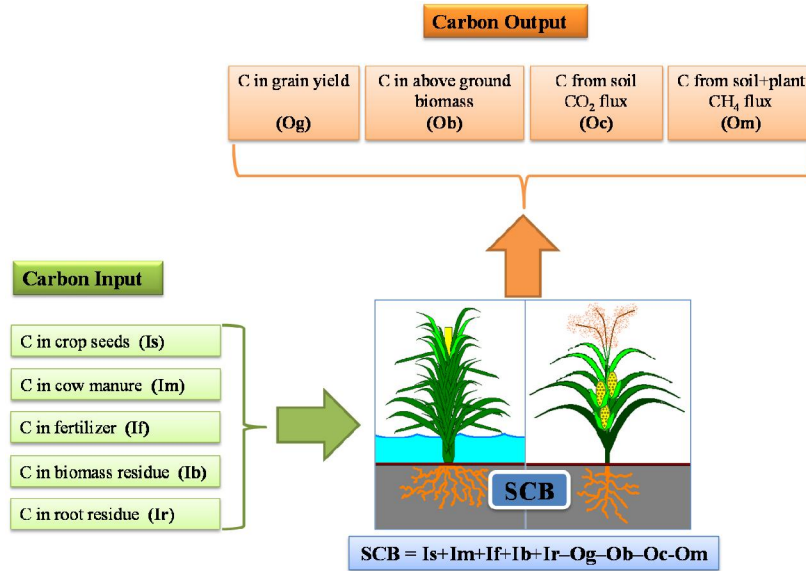
**Figure 4.1** Soil sampling at the field experiment

#### 4.2.2 Estimation of soil carbon budget

In crop land, the soil carbon budget (SCB) per crop can be estimated by integrating the amounts of net carbon supplied to the soil and removed from the soil (Nishimura *et al.*, 2008). In this experiment, net carbon supplied to the soil was estimated from the amounts of seed, manure, chemical fertilizer, straw and stubble incorporation, and root residue. Carbon removed from the field included the above ground crop biomass harvest, soil respiration as CO<sub>2</sub> emissions, and CH<sub>4</sub> emissions. Soil carbon budget can be estimated by integrating the amounts of these net carbon supply and removal, as show in Figure 4.2. The SCB was calculated by the equation (1).

$$SCB = I_s + I_m + I_f + I_b + I_r - O_g - O_b - O_c - O_m \quad \dots\dots\dots(1)$$

where,  $I_s$  is carbon supplied to the soil by seeds,  $I_m$  is carbon supplied to the soil by cow manure,  $I_f$  is carbon supplied to the soil by chemical fertilizer,  $I_b$  is carbon supplied to the soil by above ground biomass incorporation,  $I_r$  is carbon supplied to the soil by root residue,  $O_g$  is carbon removed by grain yield,  $O_b$  is carbon removed by crop biomass,  $O_c$  is carbon emitted from soil to the atmosphere in the form of CO<sub>2</sub> emission, and  $O_m$  is carbon emitted from the soil and plant to the atmosphere in the form of CH<sub>4</sub> emission. The variable descriptions of SCB calculation is presented in Table 4.1.



**Figure 4.2** The carbon dynamics in the experimental system

**Table 4.1** Terms of carbon calculations

Term	Description	Carbon Calculation (dry mass)
Is	carbon supplied to the soil by seeds	mass of seed × %C in seed
Im	carbon supplied to the soil by cow manure	mass of manure × %C in manure
If	carbon supplied to the soil by chemical fertilizer	mass of fertilizer × % C in fertilizer
Ib	carbon supplied to the soil by above ground biomass incorporation	mass of stubble × %C in crop residue
Ir	carbon supplied to the soil by root residue	mass of root × %C in root residue
Og	carbon removed by grain yield	mass of grain yield × %C in grain yield
Ob	carbon removed by crop biomass harvest	mass of crop biomass × %C in crop biomass
Oc	carbon emitted from soil to the atmosphere in the form of CO <sub>2</sub> emissions	accumulated of CO <sub>2</sub> flux × (12/44)
Om	carbon emitted from soil+plant to the atmosphere in the form of CH <sub>4</sub> emissions	accumulated of CH <sub>4</sub> flux × (12/16)
SCB	soil carbon budget (g C m <sup>-2</sup> )	Is + Im + If + Ib + Ir - Og - Ob - Oc - Om

### 4.2.3 Estimation of soil organic carbon stock

The soil organic carbon stock for each crop was estimated by the equivalent soil mass method (ESM) (Lee *et al.*, 2009). The original ESM method uses the soil mass of each soil layer sampled at the initial or original sampling time ( $t=0$ ) as the ESM for the layer. When soils are sampled to the same fixed depth layers ( $i=1, 2, \dots, n$ ) at each sampling time, soil mass is calculated as Equation (2):

$$M_i = BD_i \times T_i \times 10^4 \quad \dots\dots\dots (2)$$

where,

- $M_i$  = dry soil mass ( $\text{Mg ha}^{-1}$ )
- $BD_i$  = bulk density ( $\text{Mg m}^{-3}$ )
- $T_i$  = the thickness of the soil layer (m)
- $10^4$  = a unit conversion factor ( $\text{m}^2 \text{ha}^{-1}$ )

The fixed depth SOC stock determination of area C stock is calculated as Equation (3):

$$C_{i,\text{fixed}} = \text{conc}_i \times M_i \quad \dots\dots\dots (3)$$

where,

- $C_{i,\text{fixed}}$  = the C mass to a fixed depth ( $\text{kg C ha}^{-1}$ )
- $\text{conc}_i$  = the C concentration (C content) ( $\text{kg C Mg}^{-1}$ )
- $M_i$  = dry soil mass ( $\text{Mg ha}^{-1}$ )

The equivalent C mass ( $\text{Mg C ha}^{-1}$ ) in a soil layer is calculated using the following Equation (4-5):

$$M_{i,\text{add}} = M_{i,\text{equiv}} - M_i \quad \dots\dots\dots (4)$$

$$C_{i,\text{equiv}} = \{[C_{i,\text{fixed}} - (\text{conc}_{\text{top}} \times M_{i-1,\text{add}})] + [\text{conc}_{\text{bottom}} \times (M_{i,\text{add}} - M_{i-1,\text{add}})]\} / 1000 \quad \dots\dots\dots (5)$$

where,

- $C_{i,\text{equiv}}$  = the equivalent C mass ( $\text{Mg C ha}^{-1}$ )
- $M_{i,\text{equiv}}$  = the selected ESM ( $\text{Mg ha}^{-1}$ )
- $M_{i,\text{add}}$  and  $M_{i-1,\text{add}}$  = the additional soil masses that are used to attain the ESM ( $\text{Mg ha}^{-1}$ )
- $\text{conc}_{\text{top}}$  and  $\text{conc}_{\text{bottom}}$  = C concentration for the additional soil mass ( $\text{kg C Mg}^{-1}$ )

### 4.3 Results

Under the different four crop rotation systems in the field experiment, the results are presented the soil properties, soil carbon budget, soil organic carbon stock, and relationship of net carbon supplied to the soil and soil organic carbon stock. These results are described below.

#### 4.3.1 Soil properties

##### 4.3.1.1 Initial soil properties

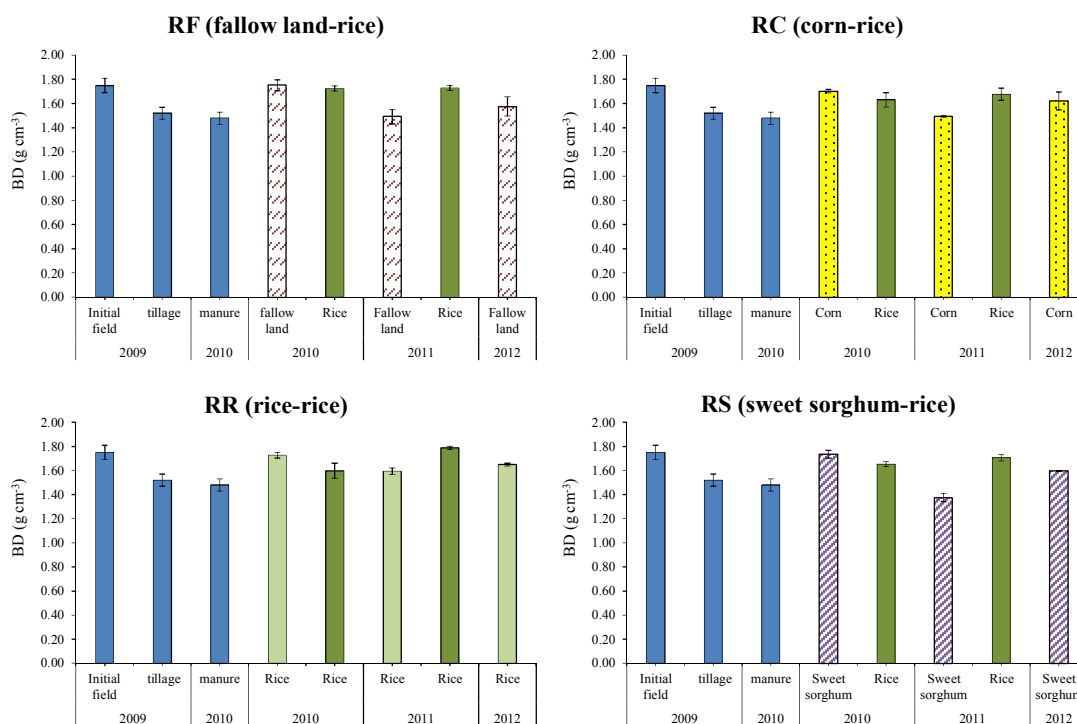
An abandoned rice field that laid fallow for 10 years before the experiments began in 2010 was used. The soil at this site is classified as Khao Yoi (Kyo) soil series described as follows: a pinkish gray (7.5YR6/2) sandy loam, many fine distinct strong brown mottles, weak medium and coarse subangular blocky structure, soft, friable, slightly sticky, slightly plastic, and very few small soft Fe and Mn nodules (LDD, 2009). The total Fe content was 3.842-77.34 g kg<sup>-1</sup> and the total Mn content was 0.08-3.09 g kg<sup>-1</sup> (Churthong, 2009). Other soil characteristics are listed in Table 4.2.

**Table 4.2** Soil properties of the abandoned rice field in the site experiment

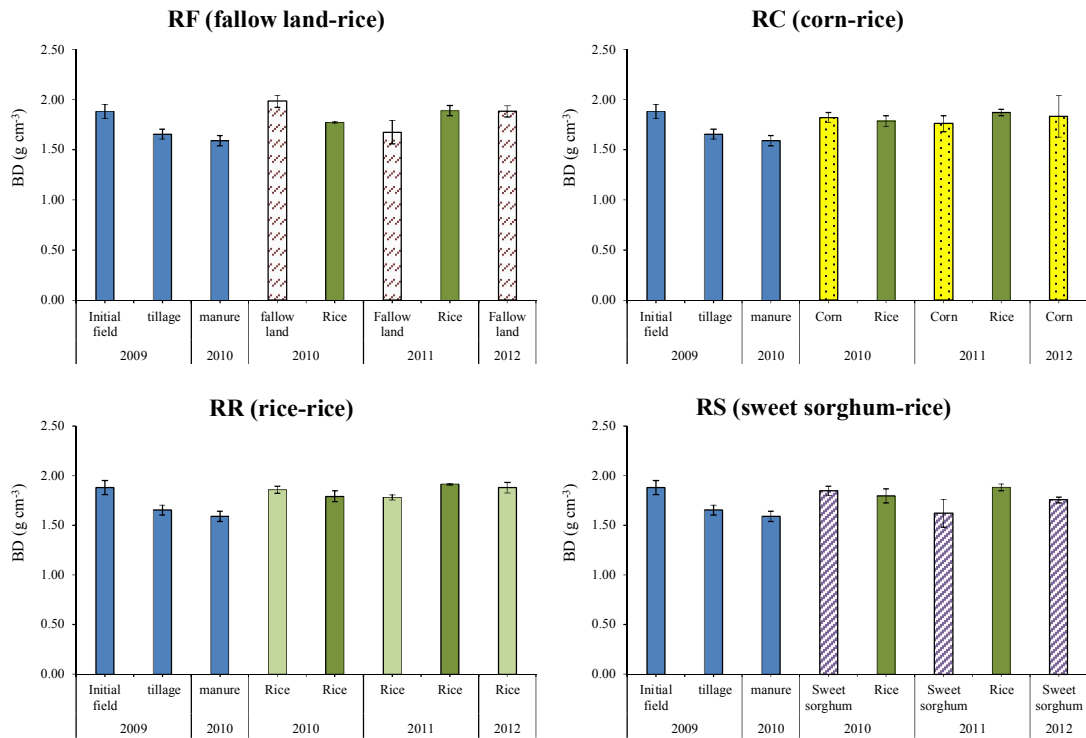
Soil properties / soil depth	0-15 cm	15-30 cm
Sand (%)	53	67
Silt (%)	45	25
Clay (%)	2	8
Soil texture	Sandy loam	Sandy loam
Bulk density (g cm <sup>-3</sup> )	1.75	1.88
Soil pH	5.8	6.2
SOM (0-15 cm) (%)	0.69	0.38
SOC (0-15 cm) (%)	0.4	0.2
Phosphorus (P-available) (mg kg <sup>-1</sup> )	4.0	2.0
Potassium (K-available) (mg kg <sup>-1</sup> )	20.0	15.0
Total N (%)	0.035	0.019

### 4.3.1.2 Soil bulk density

The two layers of the soil bulk density (BD) at the soil depths of 0-15 cm and 15-30 cm as shown in Figures 4.3 and 4.4, respectively. The soil bulk densities reduced after field preparation. At the topsoil layer (0-15 cm), the bulk density varied from 1.38-1.79 g cm<sup>-3</sup> which lower than in the subsoil layer (15-30 cm) (1.62-1.98 g cm<sup>-3</sup>), and the high bulk density usually observed after the rice cropping. The subsoil layer did not see the changing of the bulk density among the four crop rotation treatments.



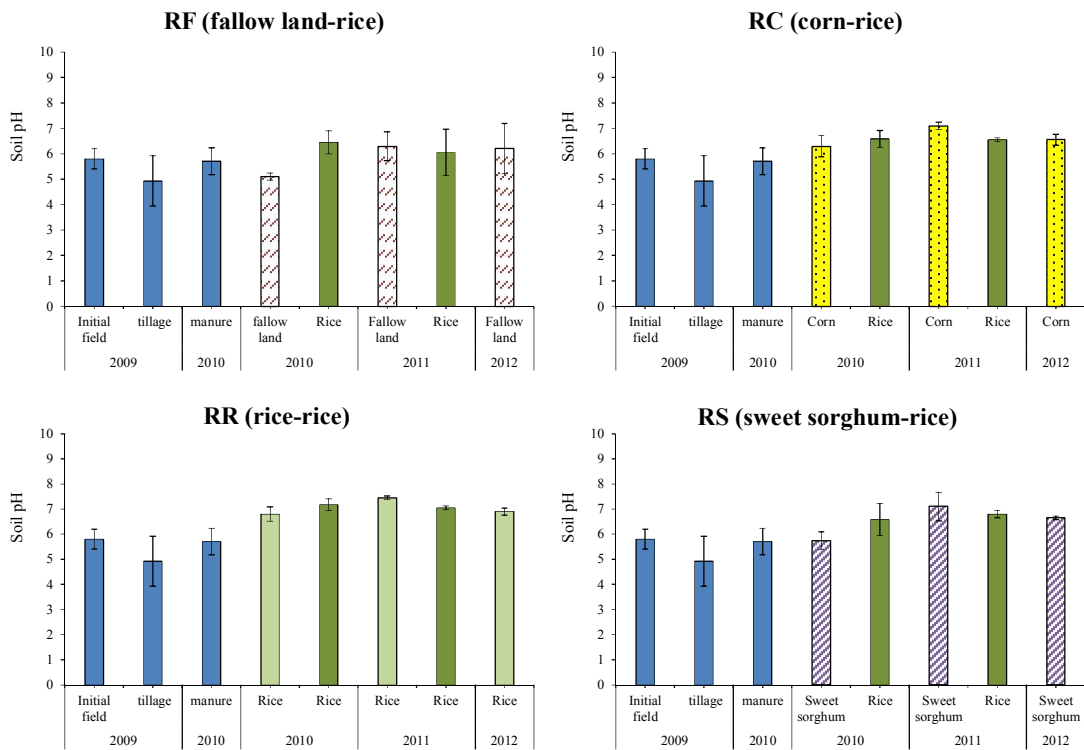
**Figure 4.3** Soil bulk density at soil depth of 0-15 cm (means  $\pm$  SD)



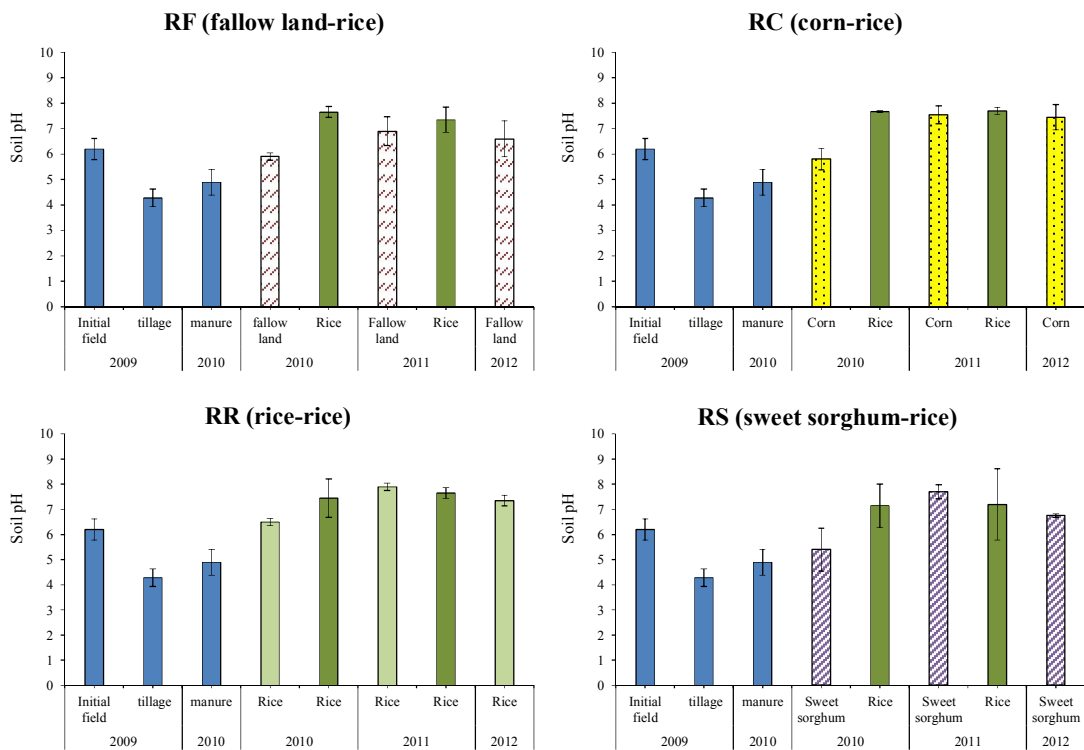
**Figure 4.4** Soil bulk density at soil depth of 15-30 cm (means  $\pm$  SD)

#### 4.3.1.3 Soil pH

The acidic soils were found in the soil prepared by tillage (pH=4.93-4.28) at both layers (Figure 4.5-4.6). After crop rotation with rice, the soils shift towards a more neutral pH. The means of soil pH after rice cropping were 6.76 in the topsoil layer and 7.42 in the subsoil layer.



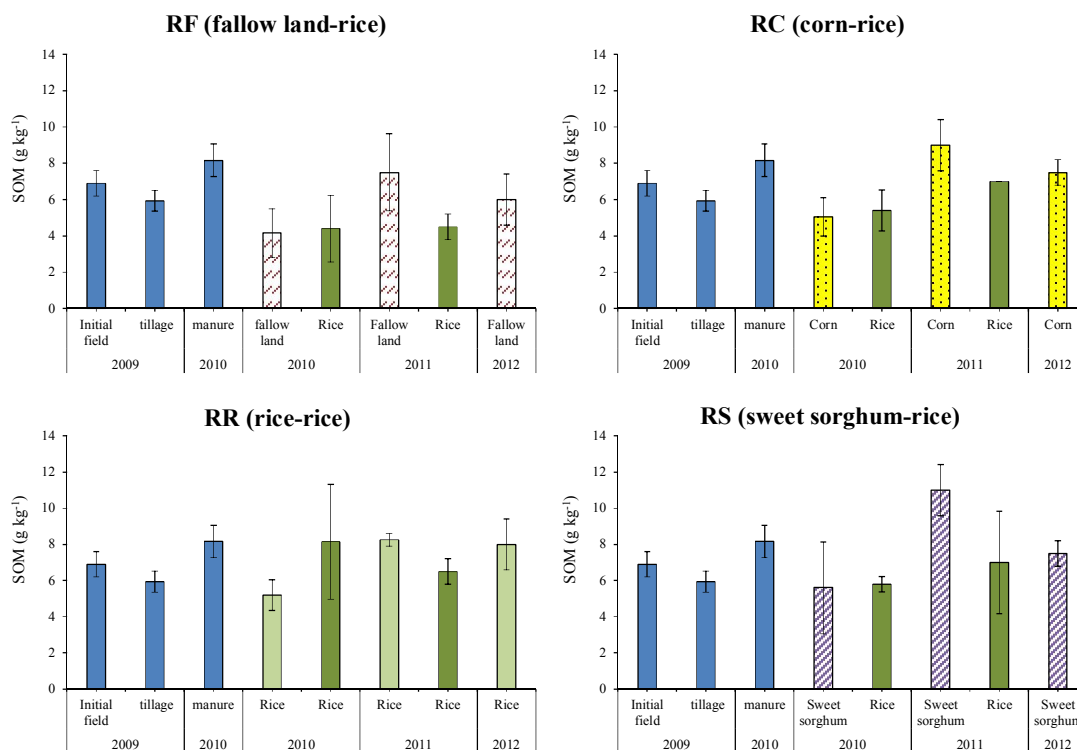
**Figure 4.5** Soil pH at soil depth of 0-15 cm (means  $\pm$  SD)



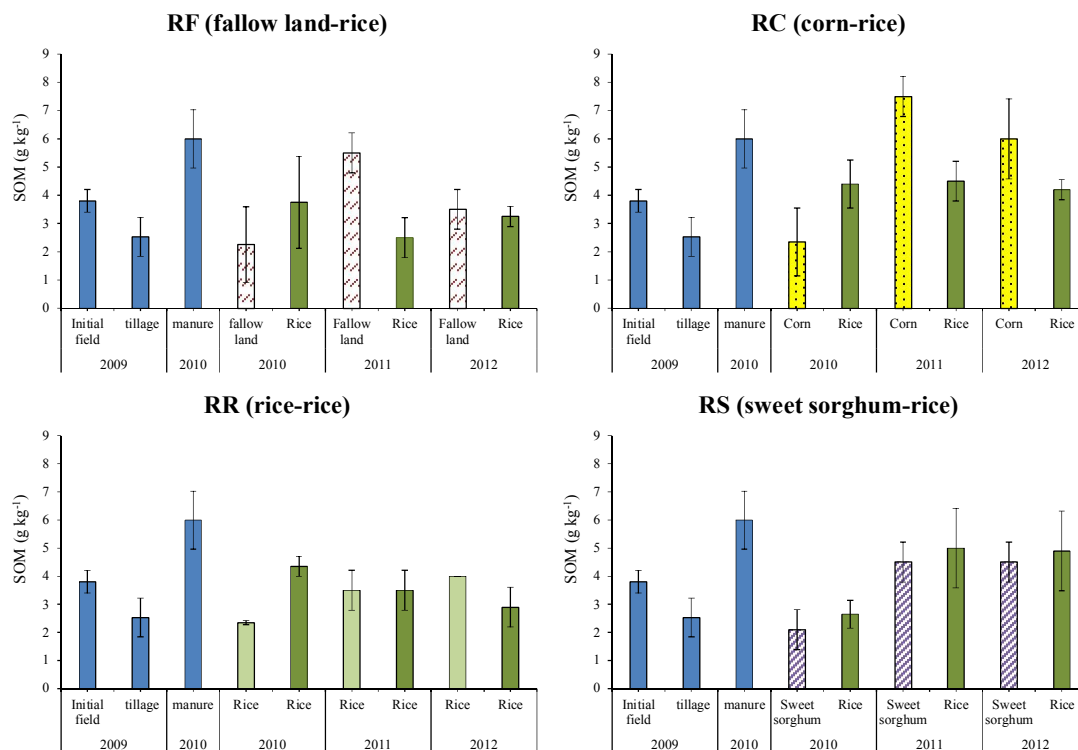
**Figure 4.6** Soil pH at soil depth of 15-30 cm (means  $\pm$  SD)

#### 4.3.1.4 Soil organic matter

The soil organic matter (SOM) varied from 4.2 to 11.0 g kg<sup>-1</sup> at 0-15 cm soil depth and 2.1 to 7.5 g kg<sup>-1</sup> at 15-30 cm soil depth (Figure 4.7-4.8). The SOM at the topsoil layer was significantly greater than those at the subsoil layer, and high SOM was also observed after energy crop cultivation and fallow land in the dry season. In the continuous rice cropping (RR), the SOMs were not different among the different rice seasons.



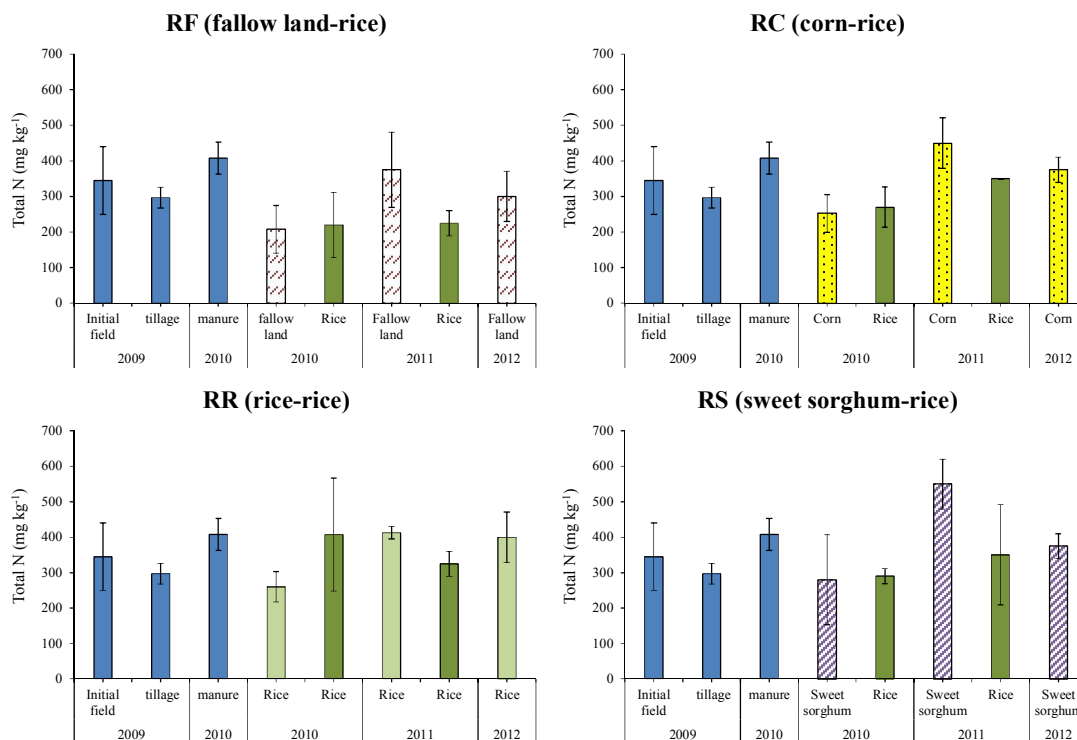
**Figure 4.7** Soil organic matter at soil depth of 0-15 cm (means  $\pm$  SD)



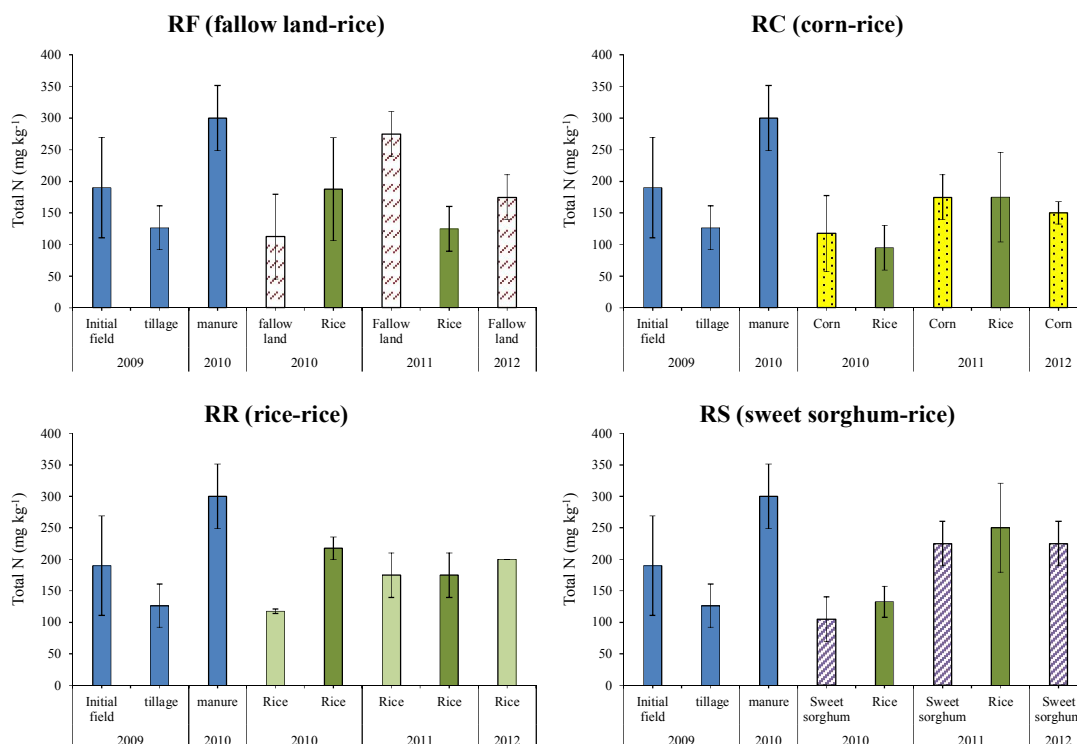
**Figure 4.8** Soil organic matter at soil depth of 15-30 cm (means  $\pm$  SD)

#### 4.3.1.5 Soil nitrogen

Figures 4.9 and 4.10 show the variation of total nitrogen (N) levels in the soil samples (soil depth 0-15 and 15-30 cm), which were collected from the four crop rotation treatments. The total soil N varied from 207-550 mg kg<sup>-1</sup> at 0-15 cm soil depth and 95-275 mg kg<sup>-1</sup> at 15-30 cm soil depth. The variations of total soil N level were similar to the soil organic matter. The higher N contents were also found in the topsoil layer and in the energy crop cultivation.



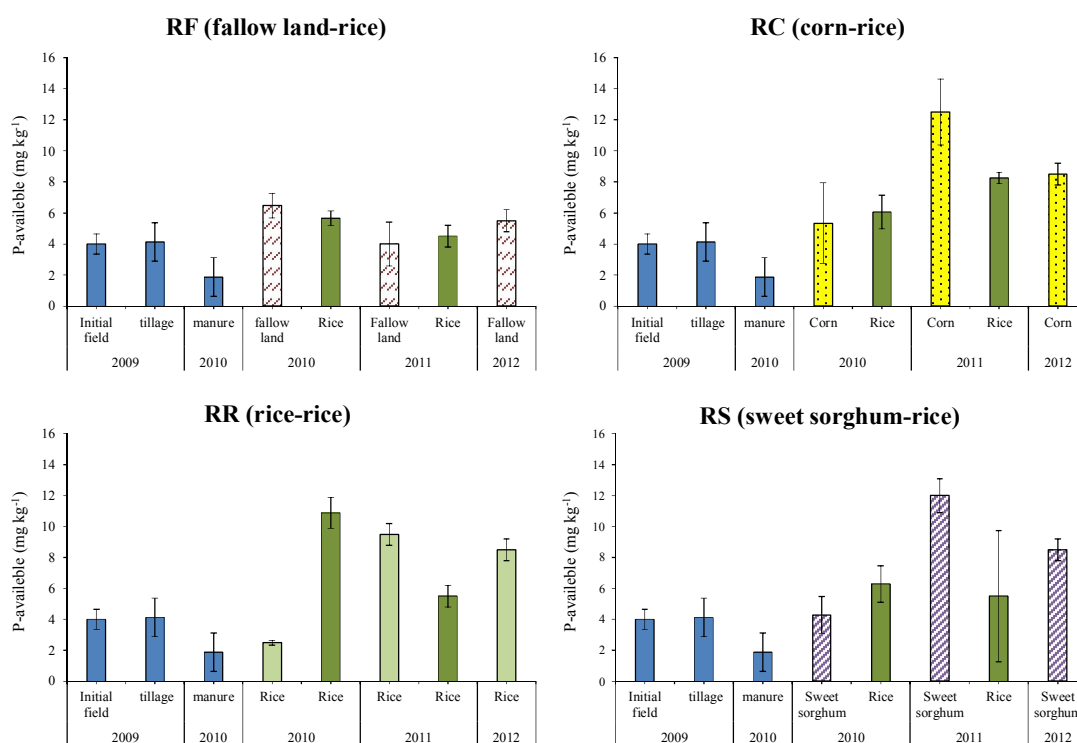
**Figure 4.9** Total nitrogen at soil depth of 0-15 cm (means  $\pm$  SD)



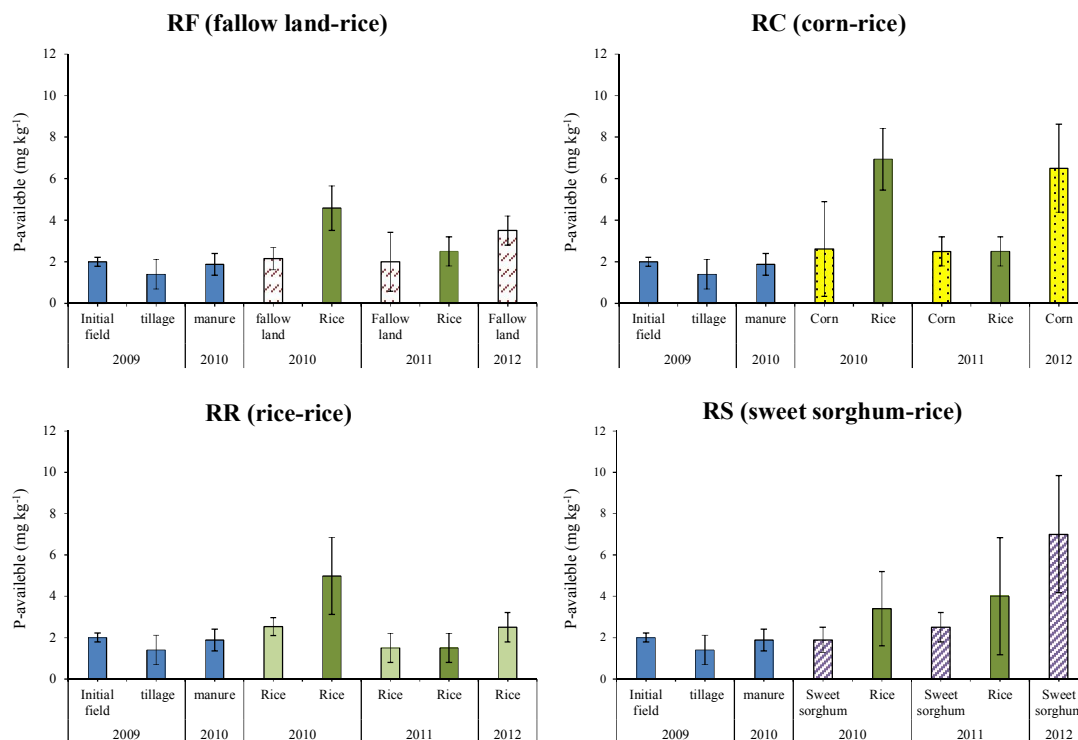
**Figure 4.10** Total nitrogen at soil depth of 15-30 cm (means  $\pm$  SD)

### 4.3.1.6 Soil phosphorus

The proportion of the phosphorus (P) that can dissolve in the soil solution and be taken up by plants is in available forms. Figures 4.11 and 4.12 show the levels of the available P in the two soil layers (0-15 and 15-30 cm) as collected from the different crop rotation systems. The available P varied from 2.5-12.5 mg kg<sup>-1</sup> in the topsoil layer and 1.5-7.0 mg kg<sup>-1</sup> in the subsoil layer. Large available P was significantly observed in the topsoil layer. In the rotations with corn and sweet sorghum were higher values of available P than in the fallow-rice.



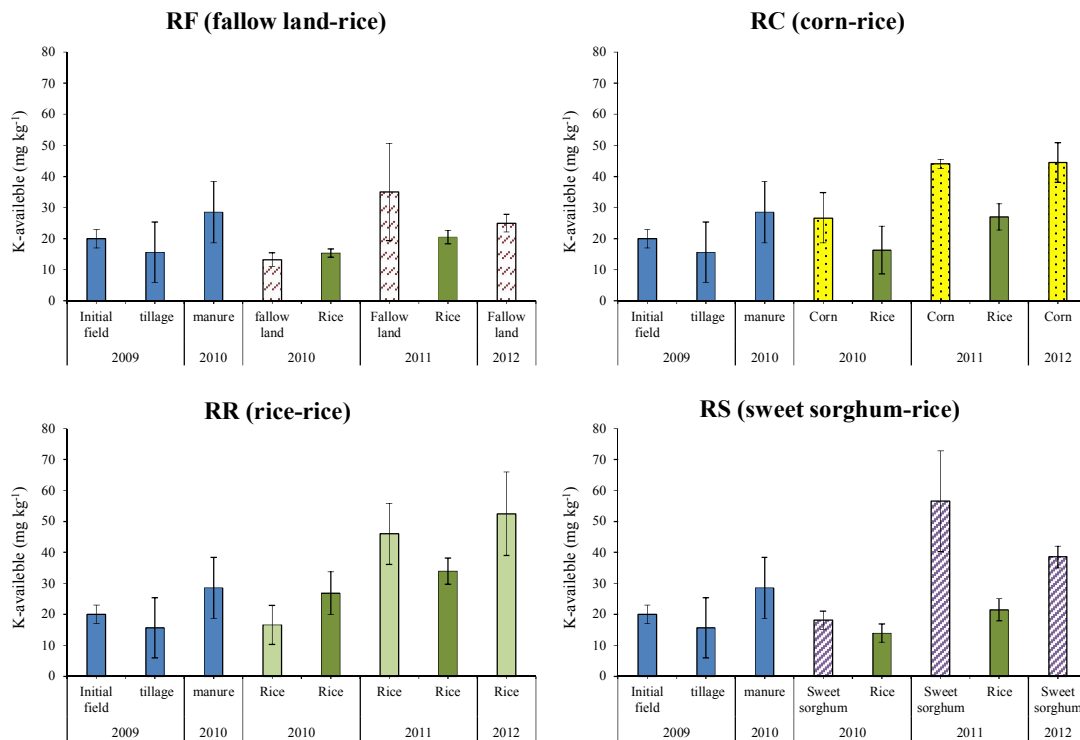
**Figure 4.11** Available Phosphorus at soil depth of 0-15 cm (means  $\pm$  SD)



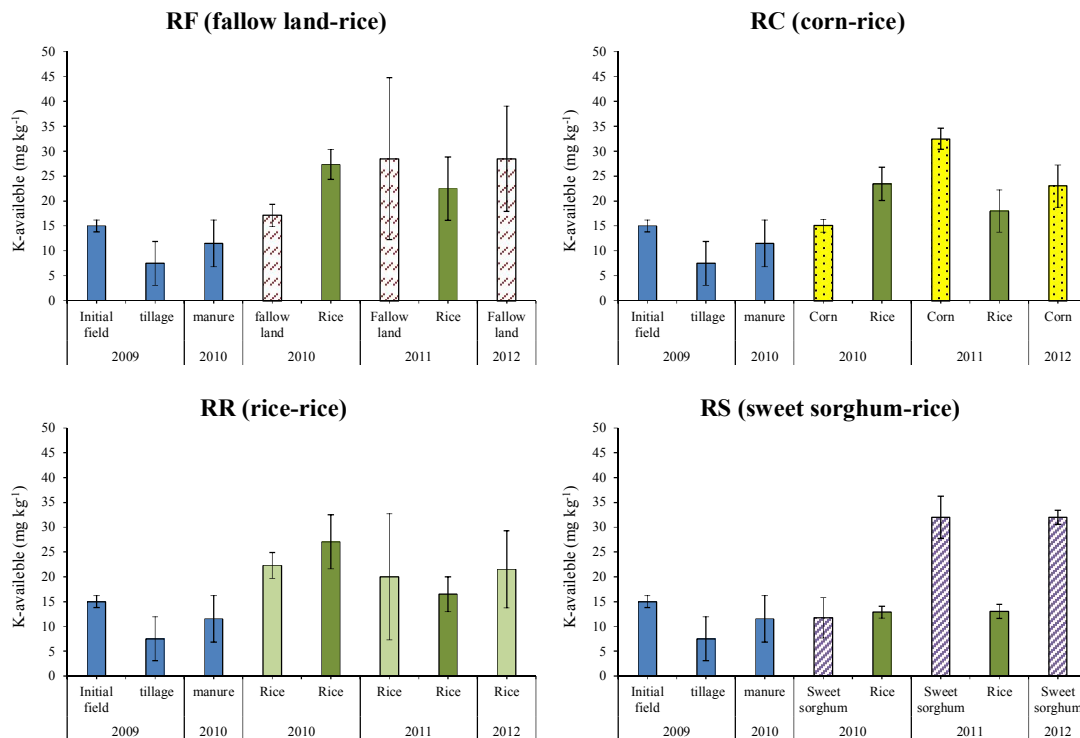
**Figure 4.12** Available Phosphorus at soil depth of 15-30 cm (means  $\pm$  SD)

#### 4.3.1.7 Soil potassium

The available potassium (K) varied from 13.3-56.5 mg kg<sup>-1</sup> at 0-15 cm soil depth and 11.7-32.5 mg kg<sup>-1</sup> at 15-30 cm soil depth (Figure 4.13-4.14). The available K was greater in the topsoil layer than in the other. The lower available K was observed in RF. The little difference was found among four rotation treatments. After seasonal cropping, the large amounts of available K were observed in the dry season in years 2011-2012.



**Figure 4.13** Available Potassium at soil depth of 0-15 cm (means  $\pm$  SD)



**Figure 4.14** Available Potassium at soil depth of 15-30 cm (means  $\pm$  SD)

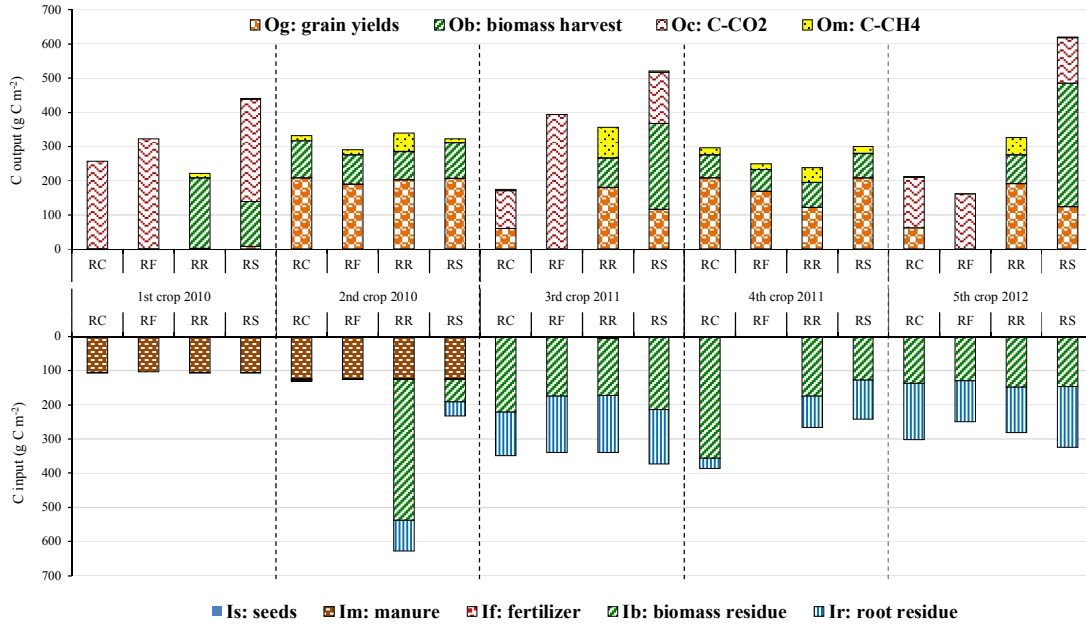
#### 4.3.2 Soil carbon budget

Table 4.3 and Figure 4.15 show the terms of carbon input and output in order to estimate the seasonal soil carbon budget (SCB) from each crop rotation system for years 2010-2012. The incorporated manure in the 1<sup>st</sup> and 2<sup>nd</sup> crops increased carbon input to the soil. The rain-fed rice residues (straw and root) in the 2<sup>nd</sup> and 4<sup>th</sup> crop were carbon input to the field in the dry season. In the dry season, soil CO<sub>2</sub> emission had strong effects to net carbon loss from the soil, especially in fallow land (RF). The most of removed carbon were observed in harvested yield and biomass (Og and Ob), especially, sweet sorghum in RS treatment was large amount C output by sorghum stalk and grain yield. The harvested rice crop in the rain-fed rice season were not significant different among four treatments.

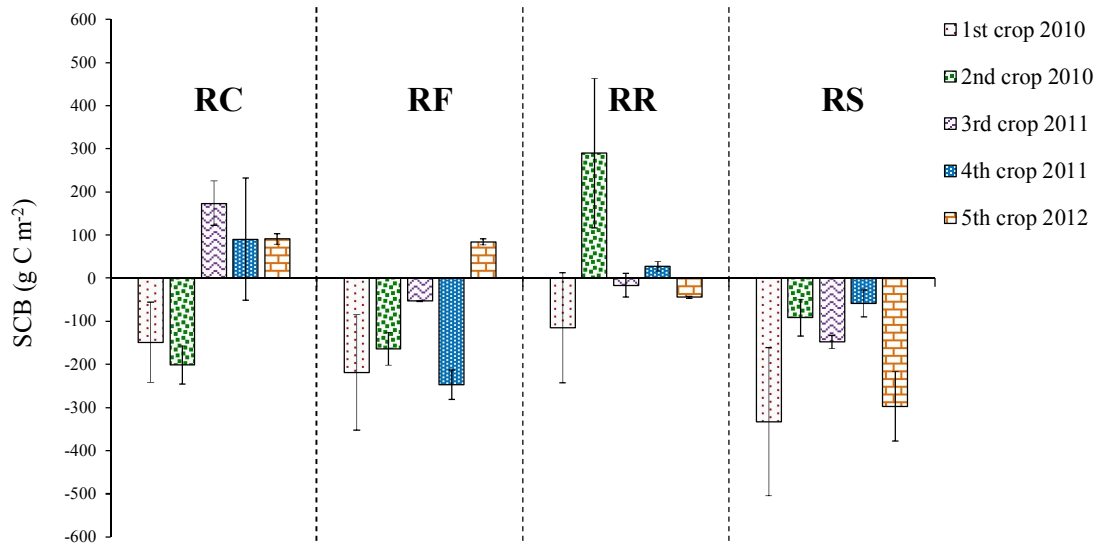
The seasonal SCBs in the four crop rotation systems shown in Figure 4.16. The SCBs varied from -333 to 289 g C m<sup>-2</sup>. In the 1<sup>st</sup> crop, the negative values of SCB were found in all treatments. The SCBs were positive values in the rotation with corn after the 3<sup>rd</sup> to the 5<sup>th</sup> crop, which indicate the carbon accumulation in the soil.

**Table 4.3** Seasonal soil carbon budgets (SCBs) in the four crop rotation systems

Treatments	C input (g C m <sup>-2</sup> )					C output (g C m <sup>-2</sup> )				SCBs
	Is seeds	Im manure	If fertilizer	Ib biomass residue	Ir root residue	Og grain yields	Ob biomass harvest	Oc C-CO <sub>2</sub>	Om C-CH <sub>4</sub>	
1 <sup>st</sup> crop 2010										
RC	0.6	104.2	2.5	0	0	1.4±0.0	0	255.1±91.0	-0.5±1.9	-148.8±92.8
RF	0	104.2	0	0	0	0	0	322.9±132.6	-0.3±1.4	-218.4±134.0
RR	0.40	104.2	2.5	0	0	2.8±0.1	205.7±121.1	0	13.7±6.3	-115.1±127.6
RS	0.4	104.2	2.5	0	0	9.2±2.3	129.4±55.7	300.2±111.4	1.4±2.2	-333.1±171.6
2 <sup>nd</sup> crop 2010										
RC	0.6	123.7	2.5	3.5±1.8	0.2±0.1	207.6±20.2	108.8±19.5	0	15.3±6.4	-201.2±44.3
RF	0.6	123.7	2.5	0	0	189.6±13.6	87.0±16.7	0	14.1±7.4	-163.9±37.8
RR	0.6	123.7	2.5	411.5±196.5	89.9±29.4	202.3±13.6	83.0±19.9	0	53.3±19.1	289.6±173.3
RS	0.6	123.7	2.5	64.3±1.7	40.5±8.1	206.7±21.1	105.3±23.8	0	11.0±7.3	-91.3±42.5
3 <sup>rd</sup> crop 2011										
RC	0.6	0	2.5	218.0±38.5	126.7±45.9	60.8±6.5	0	110.6±24.8	2.7±1.4	173.8±51.6
RF	0	0	0	173.6±33.4	166.7±43.2	0	0	393.4±74.8	0.1±1.0	-53.2±0.8
RR	0.6	0	5.0	166.2±39.7	168.5±37.9	180.8±16.7	85.5±14.5	0	90.3±19.2	-16.4±27.3
RS	0.4	0	2.5	210.4±47.7	159.3±115.0	116.6±21.0	250.6±91.6	150.4±33.9	2.9±1.1	-147.9±14.9
4 <sup>th</sup> crop 2011										
RC	0.6	0	2.5	353.5±149.4	29.7±11.1	208.5±4.4	67.5±7.9	0	19.9±6.6	90.4±141.6
RF	0.6	0	2.5	0	0	168.9±11.4	63.2±17.1	0	18.1±5.8	-247.0±34.3
RR	0.6	0	2.5	170.8±28.2	92.3±17.1	122.7±11.4	72.3±8.3	0	43.8±14.6	27.4±10.9
RS	0.6	0	2.5	125.3±45.6	112.6±39.3	208.0±21.1	71.9±25.8	0	19.9±6.8	-58.8±31.2
5 <sup>th</sup> crop 2012										
RC	0.6	0	2.5	134.7±15.5	164.6±62.9	62.0±8.1	0	149.3±57.3	0.4±0.9	90.8±12.2
RF	0	0	2.5	126.3±33.8	120.5±36.2	0	0	162.0±62.2	0.5±0.4	84.3±7.3
RR	0.6	0	2.5	144.6±17.1	133.5±36.5	191.3±13.2	85.0±17.5	0	49.4±20.4	-44.5±2.4
RS	0.4	0	2.5	143.8±51.6	177.0±38.2	124.3±19.7	361.0±101.0	133.8±48.6	1.5±1.0	-296.9±80.4



**Figure 4.15** Seasonal soil carbon inputs and outputs



**Figure 4.16** Seasonal soil carbon budgets in the four crop rotation systems (means ± SD)

### 4.3.3 Soil organic carbon stock

Soil organic carbon (SOC) stocks at a soil depth of 0-15 cm and 15-30 cm are shown in Tables 4.4-4.5 and Figures 4.17-4.20. The experiment was starting initially with an abandoned rice field. The variation and high quantity of SOC stock were clearly observed in the topsoil (0-15 cm). Field incorporated cow manure increased the SOC stocks. The lowest SOC stock was observed in fallow land of the RF plot and the highest SOC stock was observed in the corn and sweet sorghum crop rotation plots. According to the changing of rain-fed rice cultivation to energy crops, SOC stocks were significantly increased, which was observed in RC and RS treatments in the 3<sup>rd</sup> crop. Whereas, this changing was not impact in RR treatment.

In 0-15 cm soil depth, the SOC stock at the end of the 5<sup>th</sup> crop in RR, RC and RS was significantly higher than in RF (Figure 4.18) ( $P < 0.10$ ). The SOC stocks at soil depth 15-30 cm were not significantly different in RF, RR and RS at the end of the 5<sup>th</sup> crop (Figure 4.20) ( $P < 0.10$ ).

**Table 4.4** Soil organic carbon (SOC) stocks at soil depth of 0-15 cm

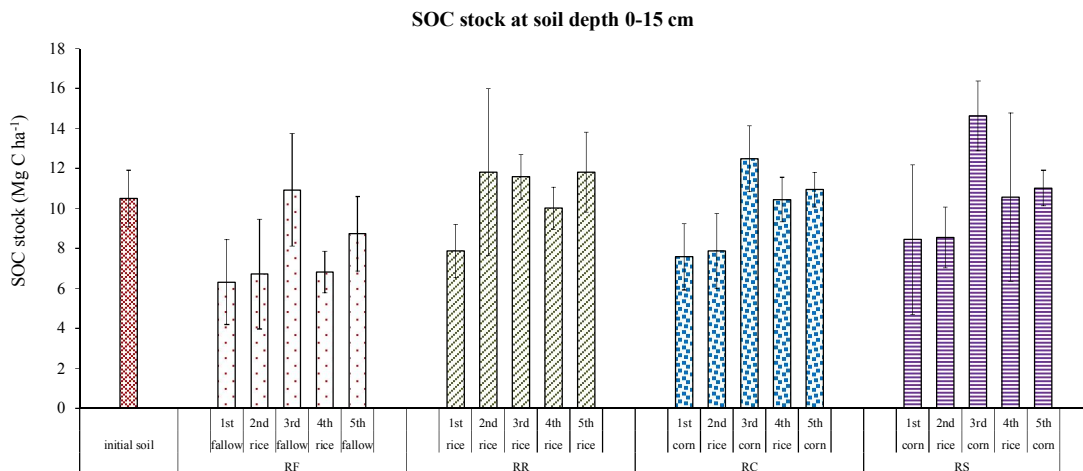
Activities before soil sampling	Activities date* dd/mm/yy	Sampling date** dd/mm/yy	SOC stock (Mg C ha <sup>-1</sup> )			
			RF	RR	RC	RS
1) Abandoned rice field		07/08/09	10.5±1.1 a	10.5±1.1 ab	10.5±1.1 ab	10.5±1.1 ab
2) Tillage	15/08/09	02/12/09	8.5±1.1 ab	8.5±1.1 ab	8.5±1.1 bc	8.5±1.1 b
3) Incorporated manure	02/01/10	03/02/10	11.9±1.5 a	11.9±1.5 a	11.9±1.5 a	11.9±1.5 ab
4) 1 <sup>st</sup> crop in 2010	07/02/10	08/07/10	6.3±2.1 b	7.9±1.3 b	7.6±1.7 c	8.4±3.7 b
5) 2 <sup>nd</sup> crop in 2010	14/08/10	14/01/11	6.7±2.7 b	11.8±4.2 a	7.9±1.9 bc	8.6±1.5 b
6) 3 <sup>rd</sup> crop in 2011	29/01/11	14/07/11	10.9±2.8 a	11.6±1.1 a	12.5±1.7 a	14.6±1.7 a
7) 4 <sup>th</sup> crop in 2011	28/08/11	08/01/12	6.8±1.0 b	10.0±1.1 ab	10.5±1.1 ab	10.6±4.2 ab
8) 5 <sup>th</sup> crop in 2012	19/02/12	03/07/12	8.7±1.9 ab	11.8±2.0 a	10.9±0.9 ab	11.0±0.9 ab

\* The date of tillage, incorporation of manure and crop planting

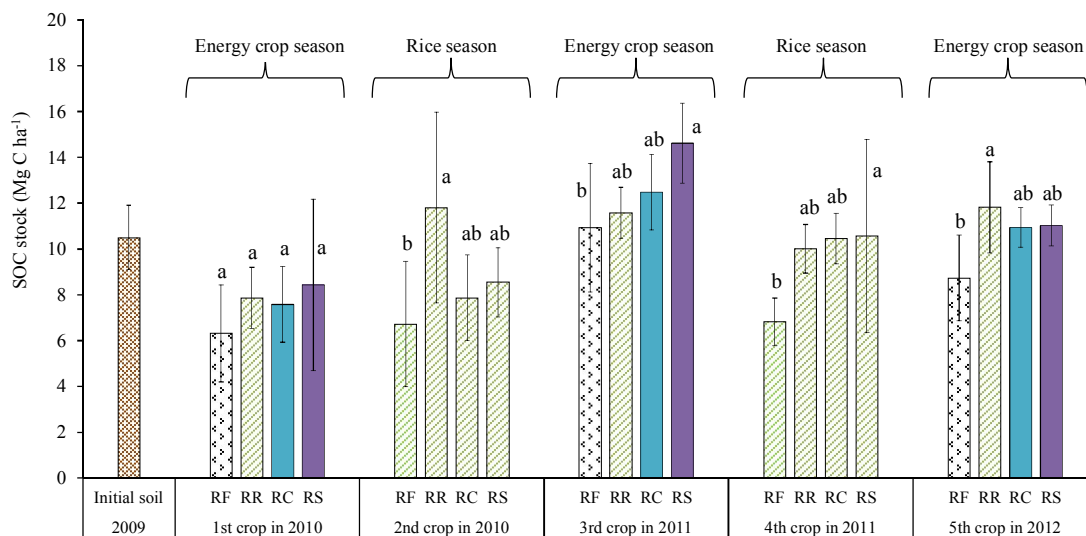
\*\* The soil sampling date after the crop activities and harvest

Values given are means ± standard deviations of three measurements.

Different letters (a, b, c) in the column denote significantly distinct categories ( $P < 0.05$ ).



**Figure 4.17** Seasonal SOC stocks at soil depth of 0-15 cm in four crop rotation treatments



The error bars given are means  $\pm$  standard deviations of three measurements. The difference letters in each crop season denote significantly different effects of crop rotation systems ( $P < 0.10$ ).

**Figure 4.18** SOC stocks at soil depth of 0-15 cm in five cropping seasons

**Table 4.5** Soil organic carbon (SOC) stocks at soil depth of 15-30 cm

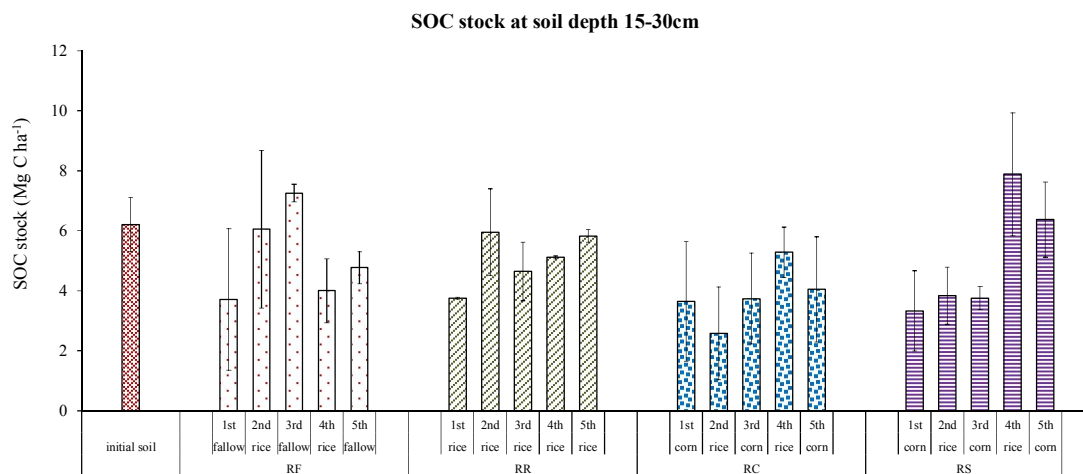
Activities before soil sampling	Activities date* dd/mm/yy	Sampling date** dd/mm/yy	SOC stock (Mg C ha <sup>-1</sup> )			
			RF	RR	RC	RS
1) Abandoned rice field		07/08/09	6.2±0.9 ab	6.2±0.9 ab	6.2±0.9 ab	6.2±0.9 ab
2) Tillage	15/08/09	02/12/09	4.0±1.1 b	4.0±1.1 c	4.0±1.1 bc	4.0±1.1 bc
3) Incorporated manure	02/01/10	03/02/10	7.9±1.5 a	7.9±1.5 a	7.9±1.5 a	7.9±1.5 a
4) 1 <sup>st</sup> crop in 2010	07/02/10	08/07/10	3.7±2.4 b	3.8±0.0 c	3.7±2.0 bc	3.3±1.3 c
5) 2 <sup>nd</sup> crop in 2010	14/08/10	14/01/11	6.1±2.6 ab	6.0±1.5 b	2.6±1.6 c	3.8±1.0 c
6) 3 <sup>rd</sup> crop in 2011	29/01/11	14/07/11	7.3±0.3 a	4.6±1.0 bc	3.7±1.5 bc	3.8±0.4 c
7) 4 <sup>th</sup> crop in 2011	28/08/11	08/01/12	4.0±1.1 b	5.1±0.1 bc	5.3±0.8 b	7.9±2.1 a
8) 5 <sup>th</sup> crop in 2012	19/02/12	03/07/12	4.8±0.5 b	5.8±0.2 bc	4.1±1.8 b	6.4±1.3 ab

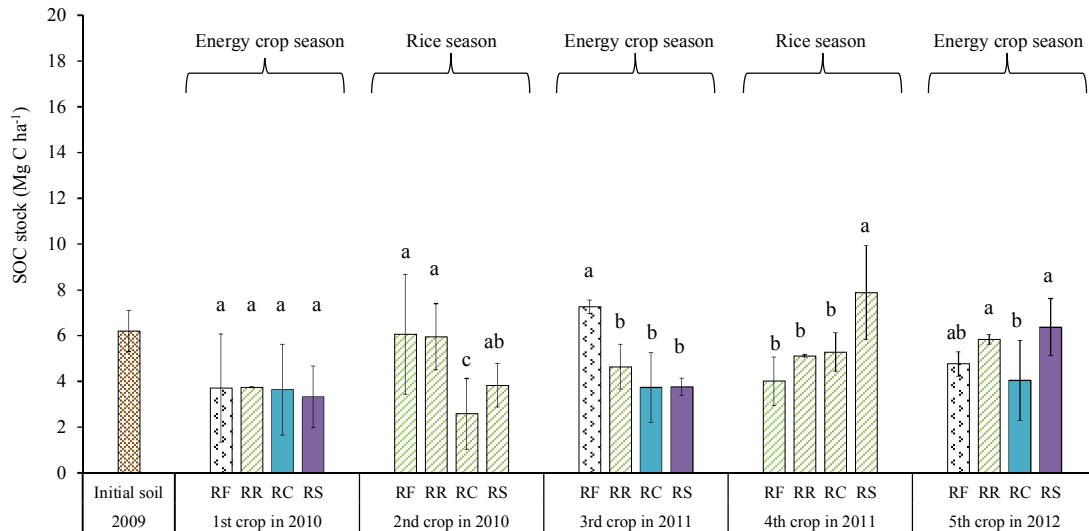
\* The date of tillage, incorporation of manure and crop planting

\*\* The soil sampling date after the crop activities and harvest

Values given are means ± standard deviations of three measurements.

Different letters (a, b, c) in the column denote significantly distinct categories ( $P < 0.05$ ).

**Figure 4.19** Seasonal SOC stocks at soil depth of 15-30 cm in four crop rotation treatments

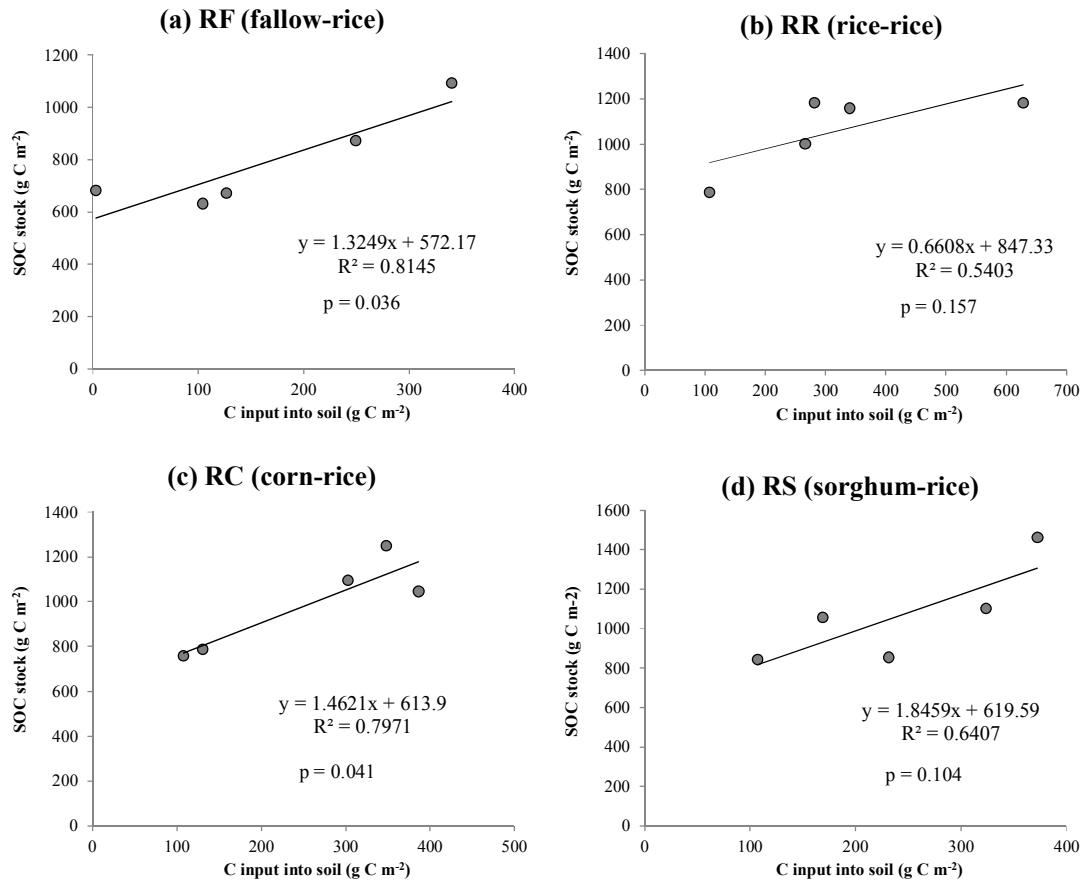


The error bars given are means  $\pm$  standard deviations of the three measurements. The difference letters in each crop season denote significantly different effects of crop rotation systems ( $P < 0.10$ ).

**Figure 4.20** SOC stock at soil depth of 15-30 cm in five cropping seasons

#### 4.3.4 Relationship of net carbon supplied to the soil and SOC stock

The soil organic carbon stock (0-15 cm soil depth) and soil carbon budget were affected by the crop management practices, including the amount of crop residue (both below and above ground), cow manure incorporation, and fertilizer application. The relationship was estimated by the correlation between the amount of carbon input into the soil and the resulting soil organic carbon stock at the topsoil layer, as shown in Figure 4.21. The results of Pearson correlations at the 0.05 level (2-tailed) in five cropping seasons showed that the rotations of RF and RC significantly affected by the amount of carbon input to the soil ( $P < 0.05$ ).



**Figure 4.21** Relationship between carbon supplied and SOC stock

## 4.4 Discussion

The difference of four crop rotation systems in the field experiment influenced soil properties, soil carbon budget and soil organic carbon stock. Their effects can be discussed in the following.

### 4.4.1 Effect of energy crop rotation on soil properties

#### 4.4.1.1 Soil bulk density

The soil bulk density (BD) were flexible across crop rotation practices by the tillage operations and crop cultivations. The soil BD reduced after field preparation because of the tillage operations destroy the soil structure and break up soil into smaller particles that provides pore space in soil (Ji *et al.*, 2013). The soil BD was high after the rice cropping, which was affected by the field puddling caused changes in soil physical properties by breaking down soil aggregates, forming hardpans at shallow depth, increased the soil bulk density (BD) (Behera *et al.*, 2009; Mousavi *et al.*, 2009; Zhou *et al.*, 2014).

#### 4.4.1.2 Soil pH

Due to the initial soil (abandoned field) being very few small soft Fe and Mn nodules, these effect to slightly acidic (pH 5.8-6.2), and pH increased with soil depth. After crop rotation with rice, the soils shift towards a more neutral pH (6.6-7.1). The increase in pH of acidic soils is mainly determined by reduction of Fe and Mn oxides, which consume H<sup>+</sup> ions, pH of soils tends to change toward neutral after flooding (Fageria *et al.*, 2011). Sahrawat (2005) also pointed that the iron reduction and carbon dioxide concentration in submerged soils play a key role in controlling the pH of submerged soils.

#### 4.4.1.3 Soil organic matter

The amounts of soil organic matter (SOM) at the two soil layers from the four crop rotation treatments were into categories of low to very low of SOM levels. The SOM at the topsoil layer was significantly greater than those at the subsoil layer due to crop residue decomposed. The SOM is usually found in the upper layer and decreases with soil depth (Craswell and Lefroy, 2001).

The first time in field preparation by tillage (107 days, 15 Aug-2 Dec 2009) reduced the SOM content in both layers, because the tillage affected on promoting decomposition rate of organic matter from abandoned land. Sapkota (2012) found that the tillage with carbon inputs are less than losses, SOM decreases for some period until it is so low that soil will not lose it anymore. One month period after cow manure incorporation,

SOM content significant improved due to supplied organic matter in the form of manure to the soil.

This experiment found the contents of SOM at the end of the rain-fed rice season in RF, RC and RS treatment are relatively lower than that in the soil at fallow period and the end of energy crop season although during rice growing season is slower decomposed under anaerobic condition. This finding also found in Ouyang *et al.* (2013) that is the SOM content in the paddy land is lower than that in the dryland. Possibly due to the incorporated the residues of corn (RC) and sweet sorghum (RS) in various amount with their lower C/N ratio than rice residue (Chapter 3, Table 3.1 and 3.8), which is indicated in easier decomposition under flooded condition during rain-fed rice season induced to ready lose and lower SOM accumulated, as same result also found in RF treatment.

According to the SOM contents at the end of energy crop seasons were higher than that in rain-fed rice season. The previous study from Fores *et al.* (1998) in Spain found that incorporated rice straw in the dry season decomposed at a rate of  $0.0075 \text{ day}^{-1}$ , and remained 75% of the biomass, 70 % of the carbon, and 50 % of the nitrogen after 139 days of decomposition. Therefore, one possible reason for this finding is the incorporated rain-fed rice residue in various amount for each treatment (Chapter 3, Table 3.1) was a short duration time decomposition (see Chapter 3, Table 3.1) before each crop cultivation in the dry season, which able to maintained the SOM.

In the continuous rice cropping (RR), the contents of SOM were not different among rice seasons because under anaerobic condition of rice growing season, the rate of decomposition of crop residue is considered to be slow (Sahrawat, 2003), leading to organic matter and carbon stored in rice soil. Ponnampereuma (1972) presented that during the rice season, the number and activity of reducing bacteria are increasing, which not only leads to the lower decomposition of organic matter and contributes to SOM accumulation but also promotes the production of toxic substances such as  $\text{CH}_4$ . Motschenbacher *et al.* (2011) suggested that the frequent cycling between anaerobic and aerobic conditions of rice-upland rotation results in a greater rate of SOM decomposition.

#### **4.4.1.3 Soil nutrients (nitrogen, phosphorus and potassium)**

The total soil nitrogen (N) was correlated with SOM content. The higher total soil N contents were also found in the topsoil layer and in energy crop season. In general, the drying soil of drainage rice field or upland field favors formation of nitrate N. Although, reduction rate of nitrate to nitrous oxide was higher during the energy crop growing season

through nitrification-denitrification process, incorporated rain-fed rice residues were decomposed under aerobic condition and additional nitrogen was applied as fertilizer during energy crop growing season (see Chapter 3, Table 3.1), resulting in high soil N after dry season cropping. Fores *et al.* (1998) found that approximately five months of rice straw decomposed in the dry season. The nitrogen remained 50%. The lower total N significantly observed after rain-fed rice harvest. The nitrate N in drying soil usually gets lost rapidly after soil flooding in rice field through leaching and denitrification, which nitrate reduces to N gas or nitrous oxide, or both (Dudal and Roy, 1993; Fageria *et al.*, 2011).

In the rotations of rice with corn and sweet sorghum were higher values of available P than in fallow-rice. The variation of soil P under the rotation of rice and upland crops influences the direct as well as the residual effects of P fertilizer (see Chapter 3, Table 3.1). As P availability changes with alternate drying and wetting, the P applied to the upland crop may have a greater residual effect on the preceding crop, whereas P applied to the rice may have less residual value for the preceding upland crop (Dudal and Roy, 1993). Fageria *et al.* (2011) pointed that phosphorus availability increased in the flooded soils because of the reduction of ferric phosphate to the more soluble ferrous form and the hydrolysis of phosphate compounds. However, the amounts of available P from this study were estimated at the low to very low level of phosphorus benefits to plants.

The amount of available K was greater than that of available P. The influence of flooding is smaller on the chemistry of K than on the chemistry of N and P (Fageria *et al.*, 2011). The lower available K was observed in RF, while RR was higher. The reducing conditions caused by flooding in rice cultivation result in a larger fraction of the K ions and the release of a relatively large amount of Fe and Mn ions and production of ammonium ions result in displacement of some of the K ions from the exchange complex to the soil solution. This may leads to greater availability of K to rice in flooded soils (Patrick and Mikkelsen, 1971; Fageria *et al.*, 2011). From the short-term experiment in this study, found the little difference available K among four rotation treatments and after seasonal cropping, the large amounts of available K were observed in the dry season in year 2011-2012. However, the amounts of available K from this study were in the low to very low ranges of potassium benefits to plants.

#### 4.4.2 Effect of energy crop rotation on soil carbon budget

The first crop in 2010 had net losses of carbon from the soil in all treatments (Table 4.3) due to a low carbon supply on the abandoned land at the beginning of the experiment. The soil CO<sub>2</sub> emission (O<sub>c</sub>) from fallow land was approximately twice than that found by Minamikawa and Sakai (2007), due to different climate and environment between Thailand and Japan. In term of carbon output, CH<sub>4</sub> emissions (O<sub>m</sub>) were generally less than that in other output components, and were similar to those reported by Nishimura *et al.* (2008) in Japanese rice fields.

The different SCBs in the rain-fed rice season depended on the type and amount of crop residue (rice, corn and sweet sorghum) supplied to the soil (I<sub>b</sub>, I<sub>r</sub>), while the carbon outputs in the form of rice production (O<sub>g</sub> and O<sub>b</sub>) were similar. The removal of crops biomass was strongly effect the soil carbon loss, especially in RS treatment, that is the most of the carbon was removed in the form of sweet sorghum stalk and grain yield.

In the first year, although cow manure was an important source of carbon input (I<sub>m</sub>) in order to improve abandoned land at the beginning of this experiment, but the crop rotations were relied upon to maintain the SCB in the second year. It is noteworthy that in the second year there were positive SCBs in the RC and RR treatments and negative SCBs in the RF and RS treatments. These SCBs were strongly affected by the crop residue management and cultivation practices as well as shown in the third year.

#### 4.4.3 Effect of energy crop rotation on soil organic carbon stock

At the beginning of the experiment, an abandoned field preparation by tillage (Aug 15, 2009 to Dec 2, 2009) caused a decrease in SOC stock (Tables 4.4 - 4.5) through increased the CO<sub>2</sub> efflux of the soil after disturbance by tillage (Calderón and Jackson, 2002). This loss was offset by the incorporation of cow manure to restore and improve the SOC stock (Shimizu *et al.*, 2009). The variations in the SOC stock at the end of each crop shown in Tables 4.4-4.5 and Figures 4.17-4.20. The results showed the changing of SOC stocks, but there are not significantly different ( $P < 0.05$ ) distinct categories by one-way ANOVA. Thereafter, the change in SOC stock in the various crop seasons and rotation crop treatments were complicated and transient, and depended on management effects on decomposition rates. However, the following overall remarks can be made.

Starting with a uniform initial SOC stock, the effect of the first year of cropping (at the end of the 2<sup>nd</sup> crop in 2010) was to maintain the SOC stock in RR and to slightly reduce it in RC and RS, a larger reduction was observed in RF. In the second year (at the end of the

4<sup>th</sup> crop in 2011), a good SOC stock was maintained by the RR, RC and RS treatments, but the RF treatment resulted in a significant SOC stock reduction. Due to the decomposition rate of the crop residues under anaerobic condition of flooded rice soil are considered to be slower than that under aerobic condition of corn and sorghum crops and fallow period, leading to more SOC stored in RR (Sahrawat, 2003). These results are in agreement with study of Saree *et al.* (2012), that is the SOC stock in continuous rice (20.88 ton C ha<sup>-1</sup>) was greater than that in corn and rice rotation (19.35 ton C ha<sup>-1</sup>). Liping and Erda (2001) measured that the soil organic matter contents in rice soil were 12-58% higher than that in upland soil. Nishimura *et al.* (2008) also found that the land use change from lowland rice to upland crop cultivation causes significant loss of carbon from cropland soil.

The relationships between carbon input to the soil and SOC stock (Figure 4.21) suggested that in all four treatments the carbon input, mainly from crop residues, improves the SOC stock. Therefore, the agricultural land management practices in order to improve SOC should select the practice that suitable supplied carbon to the soil, such as corn.

#### **4.5 Summary and Conclusion**

The rotation of rice with upland crop fields are unique from other wetland or upland soils. They are associated with frequent cycling between wetting and drying under anaerobic and aerobic conditions. Such rotations change the soil C and N cycles.

The soil physical properties and soil nutrient elements varied with different crop seasons. The soil BD was greater after the rice cropping. The initial soil (abandoned field) was slightly acidic (pH 5.8-6.2) and after crop rotation with rice, the soils shifted towards a more neutral pH (6.6-7.1). The amounts of SOM, total N, available P and available K from this study were low to very low ranges of plants benefits. SCBs were strongly affected by the crop residue management. The SOC stocks were maintained by the RR, RC and RS treatments, but significantly decreased by the RF treatment in the second year. The results showed that energy crop rotation with rain-fed rice able to improved soil fertility, SCBs and SOC stocks than single rice cropping (RF). Agricultural land management with returned crop residues is one of the suitable practices that supply C input into the soil and lead to improvement of SOC stock. Thus, the crop rotation management by rice-energy crop systems should suggest and implement for Thai farming.

## CHAPTER 5

### SHORT AND LONG TERM SIMULATIONS OF GREENHOUSE GAS EMISSIONS AND SOIL ORGANIC CARBON STOCK USING DNDC-MODEL

#### 5.1 Introduction

Agricultural activities directly produce and release the atmospheric greenhouse gases (GHG), such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) (IPCC, 2007). The land use change for agricultural propose causes an important loss of soil organic carbon (SOC) mainly in the form of CO<sub>2</sub> (Dawson and Smith, 2007). Several agricultural management practices are known to be an important factor for GHG emissions. There are highly variable so it is difficult to integrate emissions over space and time (Smith *et al.*, 2010). In short-term ( $\leq 10$  years) field monitoring of soil carbon change in continuously crop management practices was difficult to detect because the management is complex and varies with soil condition. While, long term field monitoring is well to detect the changing trend of soil carbon under different cropping system, but this need more than ten years to catch the significant change (López Garrido *et al.*, 2009). In order to long-term monitoring, it is then important to use a tool for estimate and predict GHG emissions and SOC stock change from agricultural system.

The site mode of DNDC model has been simulated for short-term and long-term changes in GHG emissions and soil organic carbon stock in the different crop rotation systems. The DNDC (Denitrification-Decompostion) model is a complex process based model of carbon (C) and nitrogen (N) biogeochemistry in agricultural ecosystems, useful for estimating both CH<sub>4</sub> and N<sub>2</sub>O emission. It was developed for predicting soil organic carbon (SOC) storage and trace gas emission including CH<sub>4</sub> and N<sub>2</sub>O fluxes from various croplands (Li *et al.*, 1994). This model was suitable for estimating the pattern of GHG emissions throughout the growing period (Li *et al.*, 2004; Babu *et al.*, 2006; Abdalla *et al.*, 2009). Simulation of soil carbon by using DNDC model has been reported by Oiu *et al.*, (2005), Shirato (2005) and Wang *et al.*, (2008).

According to the change in SOC stock in the various crop seasons and rotation crop treatments were complicated and it is not possible to explain in detail all the variations in the SOC stock, as shown in Chapter 4. Furthermore, the relationship between the amount of carbon input into the soil by crop residue and cow manure incorporation and fertilizer

application, and the resulting in SOC stock showed that the crop rotations of RF and RC significantly positive effected on SOC stock. While, the rotation of RR and RS were also correlated but not yet significant in the short-term. So, the application of DNDC model is the good option for monitoring and estimating their significant effects.

The estimation of GHG emissions and SOC stock in short and long term period by site mode of DNDC model is important keys in order to find a suitable crop management practices for mitigating GHG emissions and improving soil carbon sequestration in the long run. Therefore, this study aim to apply the site mode of DNDC model (version 93) in order to estimate and predict the variations of GHG emissions and SOC stocks in short-term and long-term under the different crop rotation systems.

## **5.2 Methodology**

The DNDC (DeNitrification-DeComposition) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agroecosystems (Li *et al.*, 1994). The DNDC model consists of four main ecological drivers, include soil sub-model, climate sub-model, vegetative sub-model and human activity (Li, 2000). This model is widely used to simulate the GHG emissions and SOC change. This study was implement the process based model (DNDC model, version 9.3) in site mode for simulated the short term and long term change of GHG emission ( $\text{CH}_4$  and  $\text{N}_2\text{O}$ ) and SOC stock under different crop rotation systems. The input parameters of DNDC model required more detail, including climate as daily air temperature and rainfall, soil properties, and cropping practices as shown in Table 5.1. The model was spin-up run with constant inputs of crop managements for 10 years in the beginning in order to achieve near-steady state in SOC pools before the simulation years.

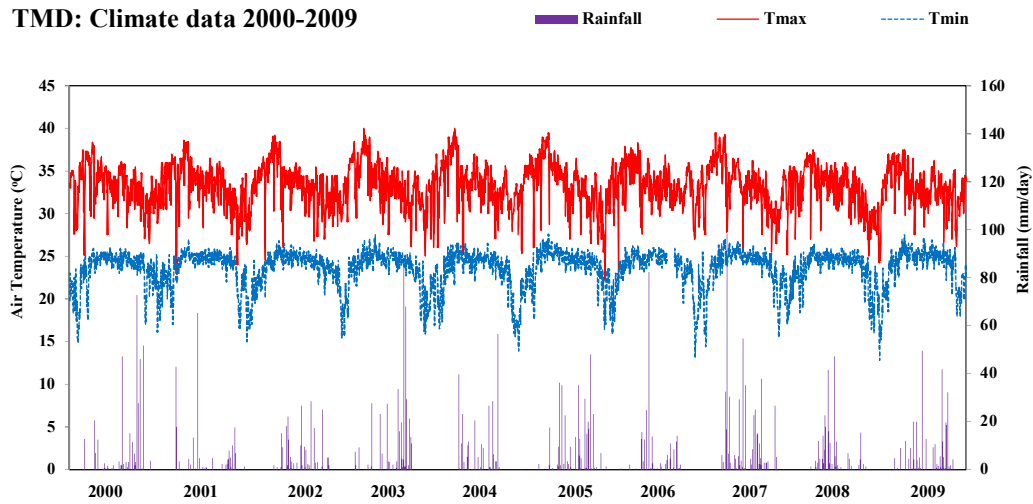
### **5.2.1 Field experimental design**

The field experiment was established in abandoned rice field at King Mongkut's University of Technology Thonburi, Ratchaburi Campus in Ratchaburi Province (see Chapter 3). The rotation systems were designed to fallow land- rice (RF), rice-rice (RR), corn-rice (RC), and sweet sorghum-rice (RS) in 2010-2011, as shown in Chapter 3.

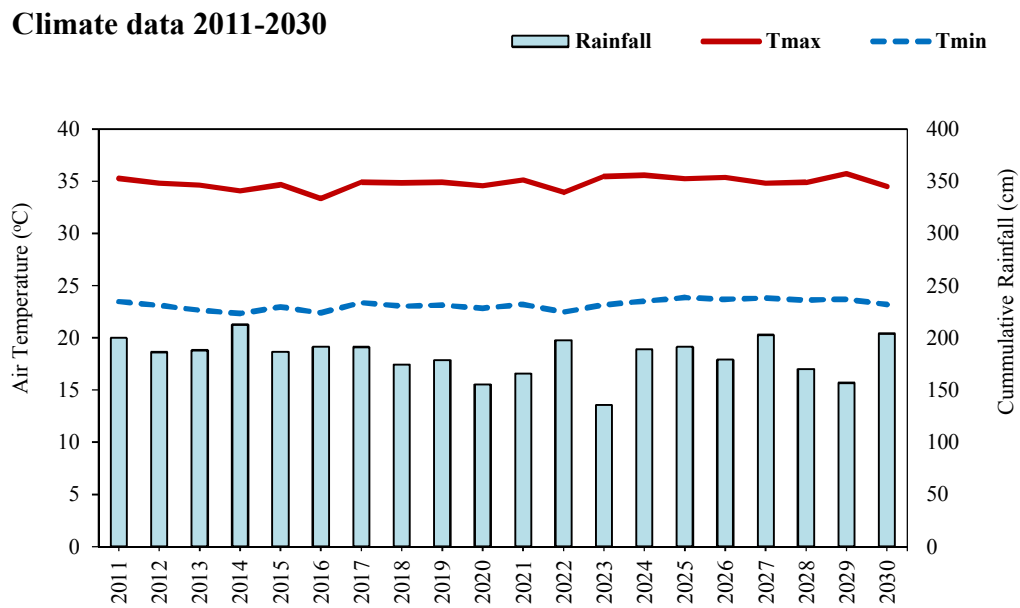
### **5.2.2 Climate dataset preparation**

This model required data of climate, soil and crop management. The climate data from Thai Meteorological Department (Ratchaburi station) which used for spin up time

simulation in period of abandoned rice field (2000-2009) (Figure 5.1) and crop experiment (2010-2011) (Chapter 3, Figure 3.2). The future simulation (2012-2030) was conducted the future climate data from PRECIS Climate model ECAM4 SRES B2 (Jones *et al.*, 2004) (Figure 5.2).



**Figure 5.1** Climate data from Thai Meteorological Department (Ratchaburi Station) during the abandoned rice field (2000-2009)



**Figure 5.2** Climate data from the PRECIS Climate model ECAM4 SRES B2 future simulation (2012-2030)

### 5.2.3 Soil and crop dataset preparation

The soil datasets consist of soil physical and chemical properties collected from field experiment and analyzed in the laboratory, as shown in Chapter 4, Table 4.2. The crop dataset included physiological data for the different cropping systems, which were collected from field experiment in years 2010 and 2011 (Chapter 3, Table 3.1). Long-term simulation used the crop dataset from year 2011 for input parameters as the based crop dataset for future projection (2012-2030) (Table 5.1).

**Table 5.1** The DNDC model input parameters of different crops grown in 2010 and 2011

Parameters	Irrigated	Corn	Sweet	Rain-fed rice
	rice		sorghum	in rotation with
	RR	RC	RS	RF, RC, RR, RS
<b>1<sup>st</sup> year experiment, 2010</b>				
Maximum crop yield (kg C ha <sup>-1</sup> )	1.00	14	92	913, 1150, 1073, 723
Fraction of Ground Residue	0.54	0.72	0.44	0.57, 0.51, 0.70, 0.58
Fraction of grain	0.0001	0.28	0.04	0.18, 0.20, 0.20, 0.13
Fraction of shoot (leaf+stem)	0.87	0.68	0.80	0.50, 0.58, 0.47, 0.58
Fraction of root	0.13	0.04	0.16	0.32, 0.22, 0.33, 0.29
<b>2<sup>nd</sup> year experiment, 2011</b>				
Maximum crop yield (kg C ha <sup>-1</sup> )	1259	608	1166	1464, 1739, 1142, 1622
Fraction of Ground Residue	0.46	0.87	0.32	0.47, 0.49, 0.53, 0.51
Fraction of grain	0.27	0.14	0.22	0.32, 0.32, 0.25, 0.29
Fraction of shoot (leaf+stem)	0.54	0.80	0.71	0.42, 0.37, 0.47, 0.40
Fraction of root	0.19	0.06	0.07	0.26, 0.31, 0.28, 0.31
<b>C/N ratio</b>				
Grain	31	25	25	31
Shoot (leaf+stem)	52	16	29	52
Root	30	14	25	30

### 5.2.4 Statistical analysis

The results from the DNDC model are tested against field observed data (see Chapter 4) to confirm the reliability. The three years measured data (2010-2012) were compared with simulation results under different crop rotation systems. The error in difference between simulation and observation was determined by the sample correlation coefficient ( $r$ ), the relative error ( $E$ ) and the root mean square error (RMSE), using the following equations:

$$r = \frac{\sum_{i=1}^n (V_{ob} - \bar{V}_{ob})(V_{mo} - \bar{V}_{mo})}{\sqrt{[\sum_{i=1}^n (V_{ob} - \bar{V}_{ob})^2][\sum_{i=1}^n (V_{mo} - \bar{V}_{mo})^2]}} \dots\dots\dots(1)$$

$$E = \frac{100}{n} \times \sum_{i=1}^n \frac{V_{ob} - V_{mo}}{V_{ob}} \dots\dots\dots(2)$$

$$RMSE = \frac{1}{n} \sum_{i=1}^n (V_{ob} - V_{mo})^2 \dots\dots\dots(3)$$

- Where,
- $V_{ob}$  = the observed values
  - $V_{mo}$  = the simulated values from DNDC model
  - $\bar{V}_{ob}$  = the mean of the observed values
  - $\bar{V}_{mo}$  = the mean of the simulated values from DNDC model
  - $n$  = the number of the observed and simulated data

In general,  $r$  value closest to 1 indicates that the model matches the pattern of the observations. An absolute value of  $E$  is  $< 5\%$ , indicates that the modeling results are good. The smaller RMSE value is the greater prediction accuracy (Smith *et al.*, 1997; Katayanagi *et al.*, 2012; Mu *et al.*, 2014).

The coefficient of determination ( $R^2$ ) was also used in determining the degree of linear-correlation of field observation and model simulation data

## 5.3 Results

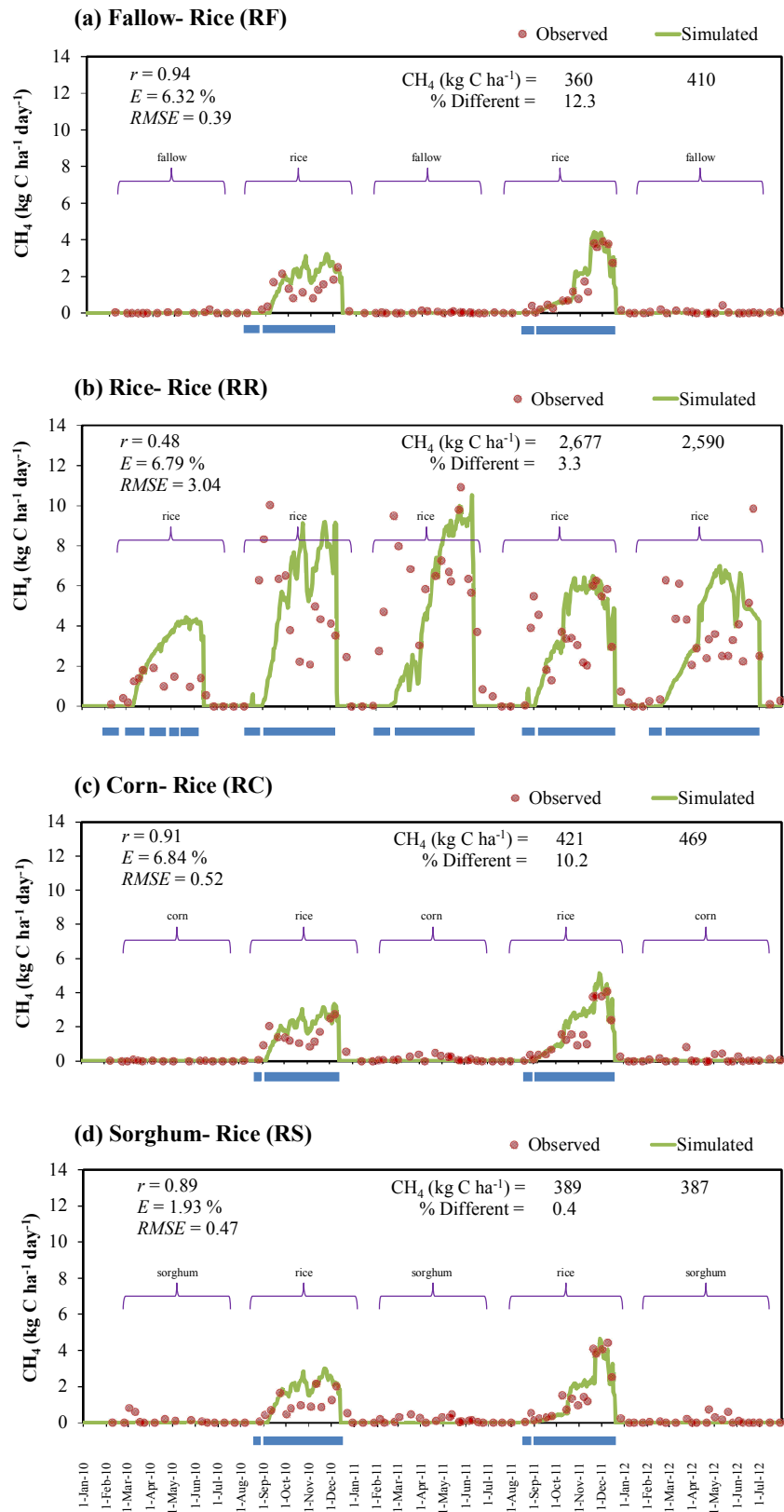
Under the different of four crop rotation systems in the field experiment, the results are presented the GHG emissions during crop experiment and future prediction. Spin-up time simulation of SOC storage in abandoned rice field, and Soil organic carbon change during crop experiment and future prediction. These results are described below.

### 5.3.1 Greenhouse gas emissions during crop experiment and future prediction

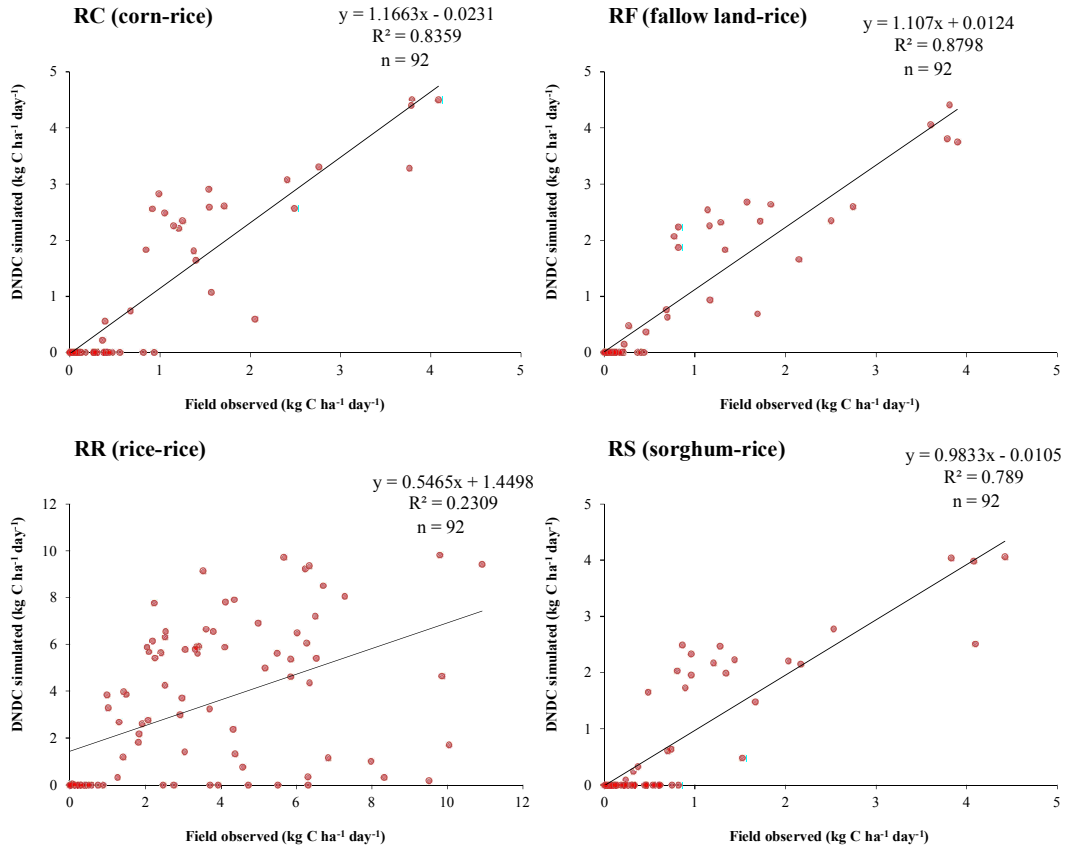
#### 5.3.1.1 CH<sub>4</sub> emissions

Seasonal CH<sub>4</sub> emissions from the rotation of energy crops and rice system were simulated practically by site mode of DNDC (version 93). There were some differences in the daily average CH<sub>4</sub> emission values. DNDC simulation showed that the seasonal variations of CH<sub>4</sub> emission (Figure 5.3) were significant higher during the rice-growing season but fewer during the fallow, corn and sorghum growing season. Simulated daily average CH<sub>4</sub> emission values ranged from zero before and after flooding to a maximum of 10.52 kg C ha<sup>-1</sup> day<sup>-1</sup>. Simulated CH<sub>4</sub> emission were validated with observed data. DNDC model found good correlation coefficient (r) in RF, RC and RS by 0.94, 0.91, 0.89, and small relative error (E) by 6.32, 6.84, 1.93%, and root mean square error (RMSE) by 0.39, 0.52, and 0.47, respectively. The results also found abundant positive linear relationships (Figure 5.4), which indicated that the DNDC model able to capture the overall trend of the daily CH<sub>4</sub> emissions in the rotation of energy crops in rice field. The different amounts of CH<sub>4</sub> emission of RF, RC and RS between observed and simulated data was 0.4-12.3%. There simulated results were indicated that DNDC model not only good agreement in quality but also well in quantity estimation. In RR cropping system, the model failed to capture the pattern of daily average CH<sub>4</sub> emission (r = 0.48, E= 6.79%, and RMSE= 3.04) but total emissions were in good agreement between observed and simulated values (3.3% different).

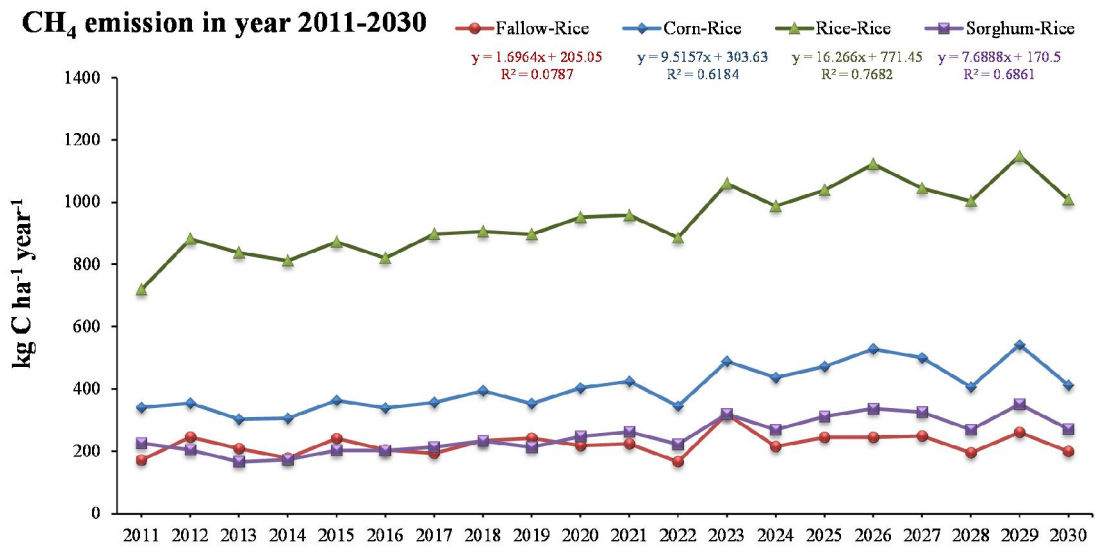
The 20-year simulation for predict an annual CH<sub>4</sub> emissions in the future under different cropping systems as shown in Figure 5.5. Annual CH<sub>4</sub> emission varies from 153.43 to 1,328.49 kg C ha<sup>-1</sup> year<sup>-1</sup>. In the long term of 20-year, the selected energy crop with corn and sweet sorghum could reduce CH<sub>4</sub> emission by 72% and 80%, respectively when compared with continues of rice cultivation (RR). Relationship between annual CH<sub>4</sub> emission and yield grain C in 20 years simulation, as shown in Figure 5.6. The results showed that the crop rotation with corn and sweet sorghum increased grain yield and reduced CH<sub>4</sub> emission in long term simulation.



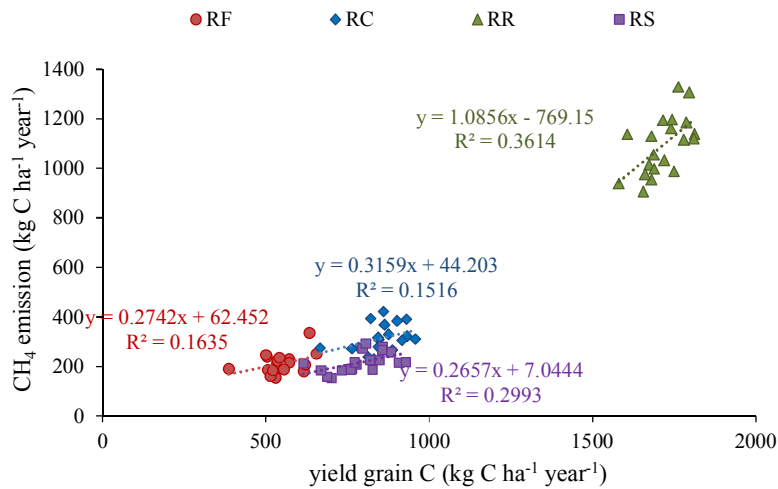
**Figure 5.3** CH<sub>4</sub> emissions and validation of crop experiment and DNDC model



**Figure 5.4** Correlation between daily CH<sub>4</sub> emissions from field observation and DNDC simulation



**Figure 5.5** Long-term simulation of annual CH<sub>4</sub> emissions in 2011-2030

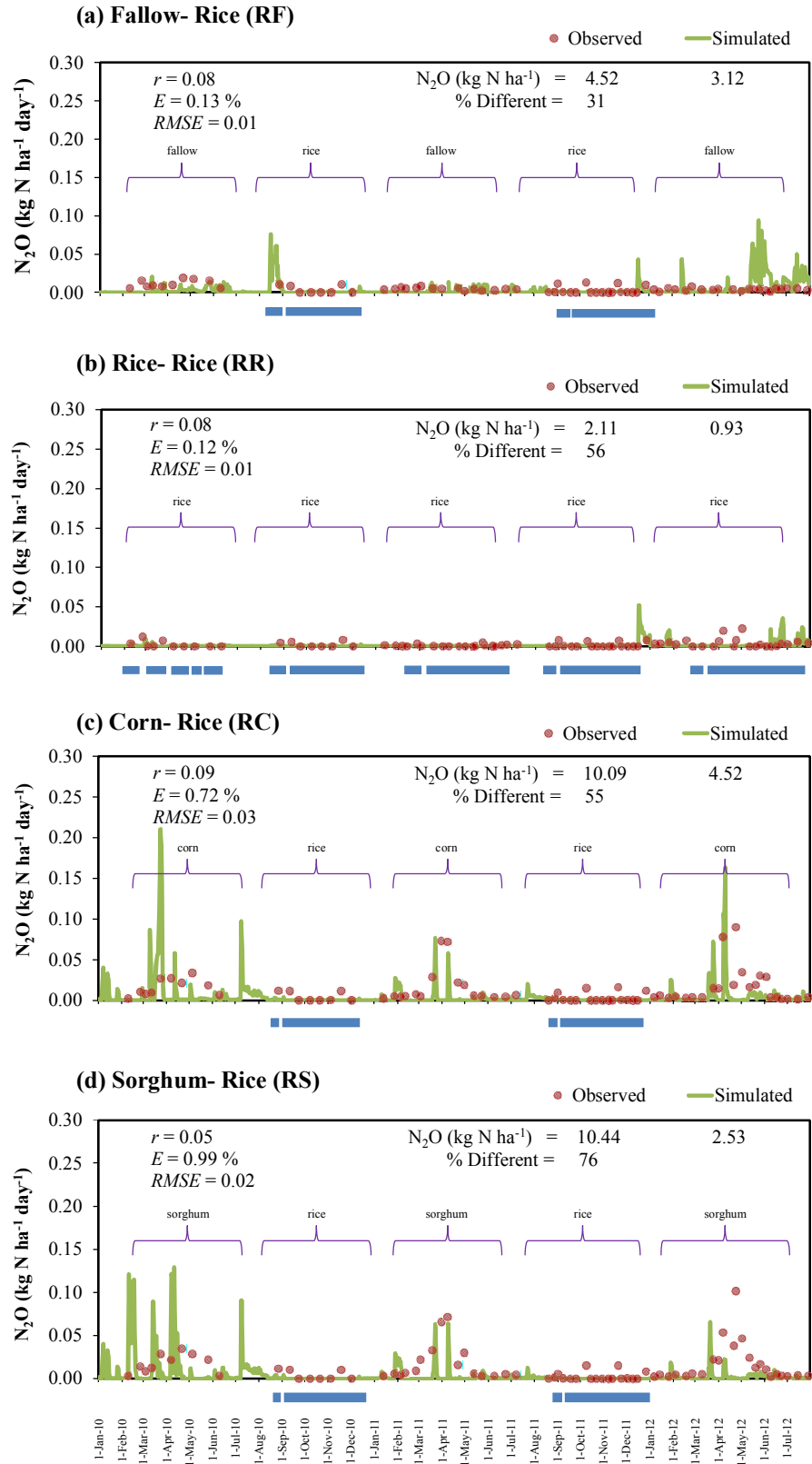


**Figure 5.6** Relationship between annual CH<sub>4</sub> emissions and yield grain C (20 years)

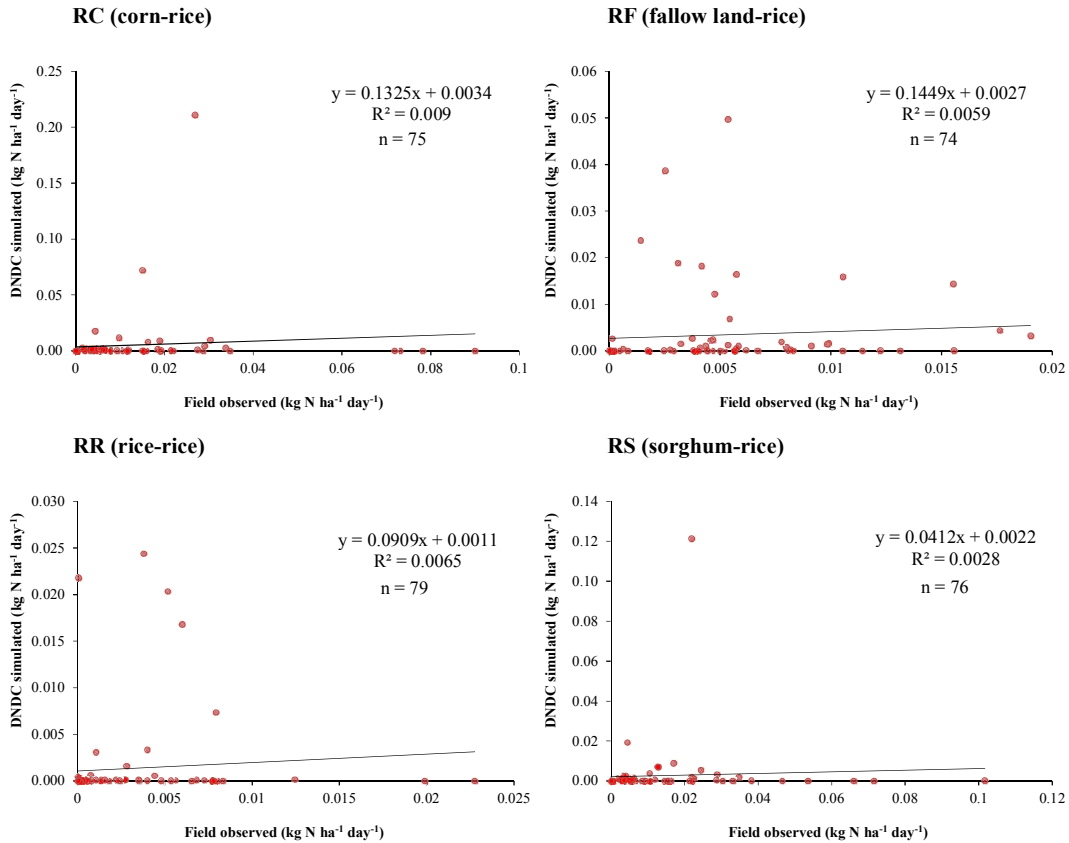
### 5.3.1.2 N<sub>2</sub>O emissions

DNDC simulation show the seasonal variations of N<sub>2</sub>O emissions (Figure 5.7), which were significant higher during fallow period, corn and sorghum growing season. During the rice-growing season, the small N<sub>2</sub>O peaks were observed at the beginning without flooding and harvest period. In year 2010 of RC and RS treatments, the N<sub>2</sub>O was extreme peaks due to nitrogen fertilizer application. Simulated daily average N<sub>2</sub>O emission values ranged from 0 to 0.211 kg N ha<sup>-1</sup> day<sup>-1</sup>. In validation, the values of N<sub>2</sub>O emission from observed and simulated were not well prediction with very low correlation coefficient ( $r = 0.05-0.09$ ) in all treatments. Although, the relationships between daily N<sub>2</sub>O emissions from field observation and DNDC simulation were positive correlation (Figure 5.8), but there were not well in order to validation. The amounts of N<sub>2</sub>O emission from the field observation were higher than the model simulation, which showed the underestimate of the model. The percentage different between observed and simulated data of N<sub>2</sub>O emissions were also in large, there varies from 31-76%. There simulated results were indicated that DNDC model failed agreement in both quality and quantity estimation of N<sub>2</sub>O emission.

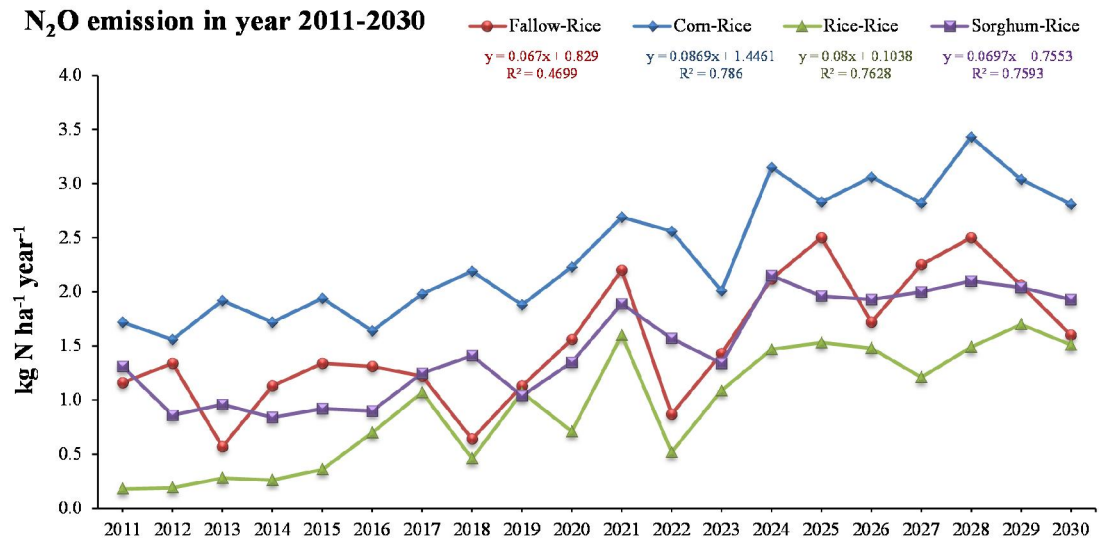
Long-term simulation of annual N<sub>2</sub>O emissions were dissimilar patterns with CH<sub>4</sub> emissions (Figure 5.9). The values varies from 0.18 to 3.43 kg N ha<sup>-1</sup> year<sup>-1</sup>. In double cropping of rice (RR), N<sub>2</sub>O emissions was significant lowest, while the rotations with corn and sweet sorghum were higher. In all crop rotation with rice, an increased yield grain significant correlated with N<sub>2</sub>O emission in long term simulation (Figure 5.10).



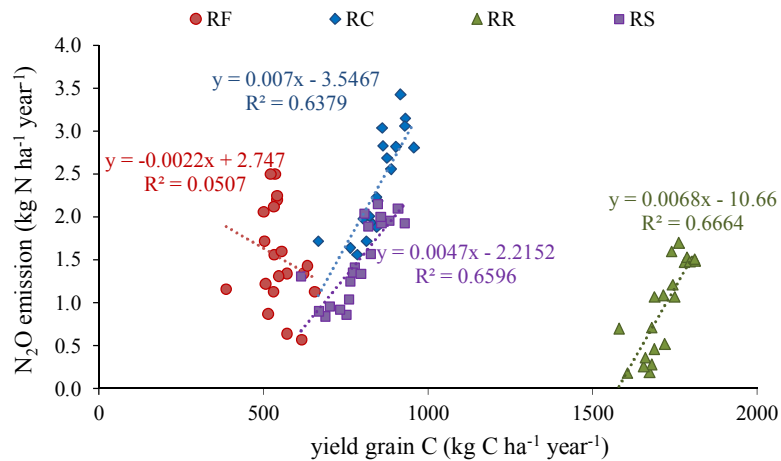
**Figure 5.7** N<sub>2</sub>O emissions and validation of crop experiment and DNDC model



**Figure 5.8** Correlation between daily N<sub>2</sub>O emissions from field observation and DNDC simulation



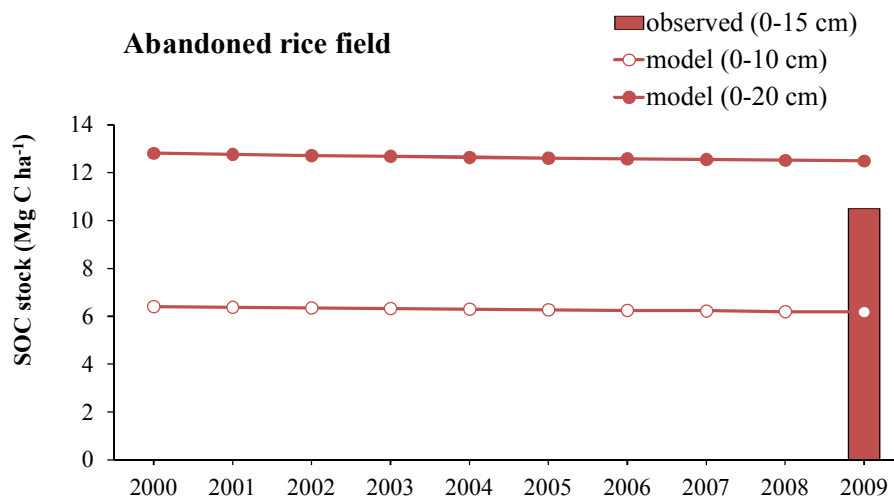
**Figure 5.9** Long-term simulation of annual N<sub>2</sub>O emissions in 2011-2030



**Figure 5.10** Relationship between annual  $N_2O$  emissions and yield grain C (20 years)

### 5.3.2 Spin-up time run for initial soil carbon pool in abandoned rice field

The spin-up time simulation in abandoned rice field period, as shown in Figure 5.11. The simulated data was showed the SOC stock at soil depth 0-10 cm and 0-20 cm, while field observed data was measured at soil depth 0-15 cm. However, the spin-up results found that the amounts of SOC in both layers were close to the equilibrium. The SOC pool before crop experiment able to use for SOC stock simulation.

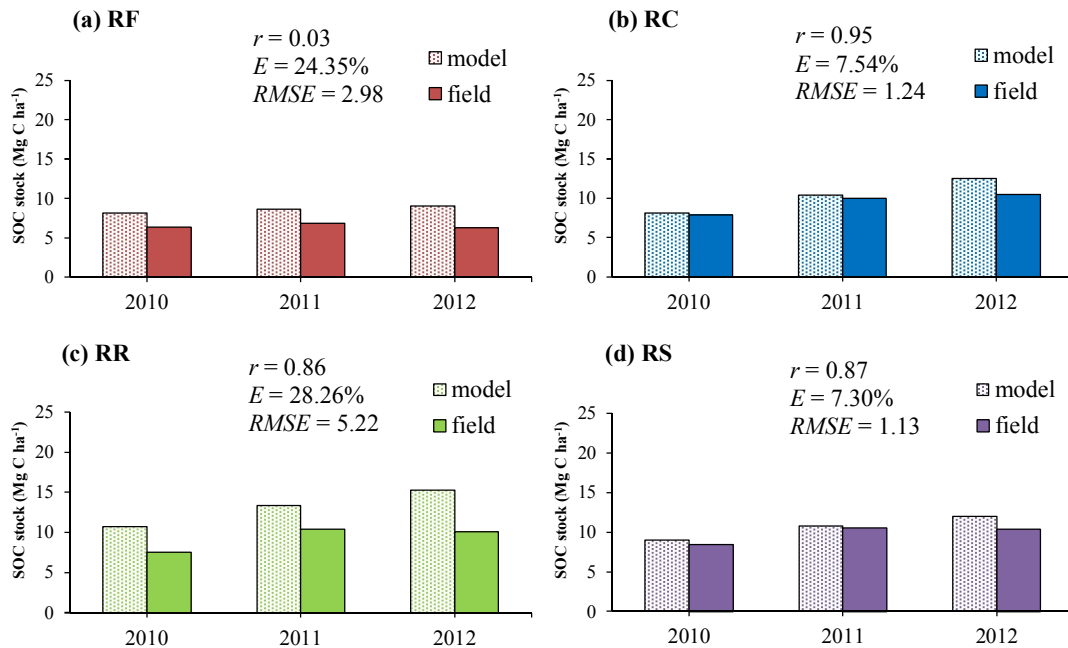


**Figure 5.11** Spin-up time simulation of SOC stock in abandoned rice field 2000-2009

### 5.3.3 Soil organic carbon changes during crop experiment and future prediction

The simulated SOC stock (0-10 cm) was reliable with the field measured values (0-15 cm) from 2010-2012 (Figure 5.12). The correlation coefficients ( $r$ ) between simulated and observed values for RF, RC, RR and RS were 0.03, 0.95, 0.86 and 0.87, respectively. Relative error ( $E$ ) values were low in RC (7.54%) and RS (7.30%), whereas RF and RR were 24.35 % and 28.26 %, respectively. The low values of RMSE in RC and RS was 1.24 and 1.13, respectively and high values were 2.98 for RF and 5.22 for RR. Overestimation of SOC stock was observed in RF and RR, especially in year 2012.

The SOC stock at 0-10 cm soil depth were simulated under different crop rotation systems (RF, RC, RR and RS) and crop management practices from 2009-2030 (Figure 5.13). The range of these simulated was 8.09-31.42 Mg C ha<sup>-1</sup>. For long-term predictions, SOC stocks in all crop rotation systems constantly increased with simulation year. In long term (2009-2030) prediction, SOC sequestration in RR, RC and RS was higher than RF by 72, 60 and 42%, respectively. In crop rotations of RR, RC and RS, an increased yield grain C also significant correlated with SOC stock in long term simulation (Figure 5.14).



**Figure 5.12** Validation of annual SOC stock from field observation and DNDC model in year 2010-2012

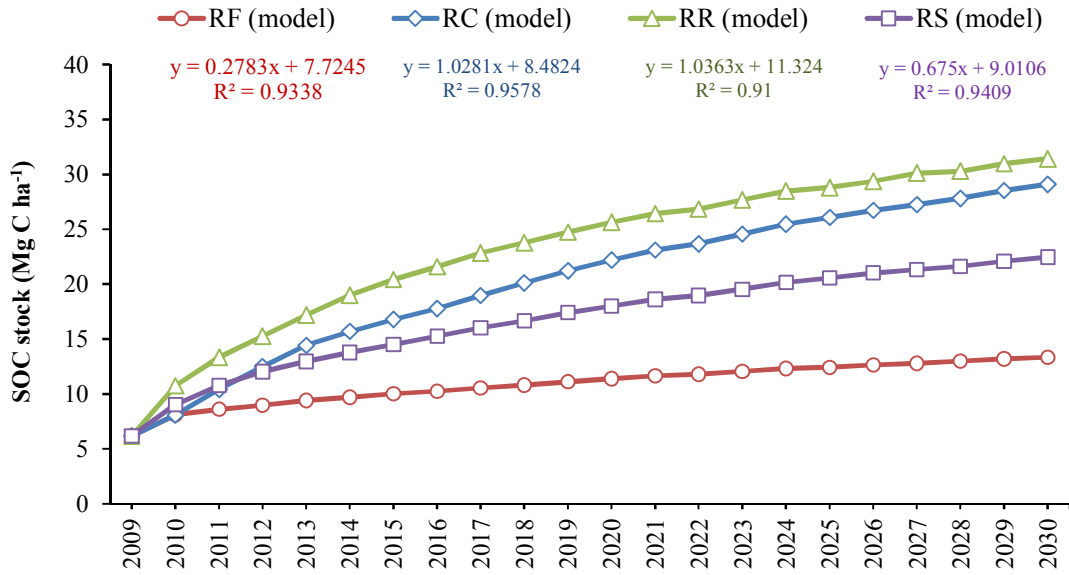


Figure 5.13 Long-term simulation of annual SOC stock (0-10 cm) from 2009 to 2030

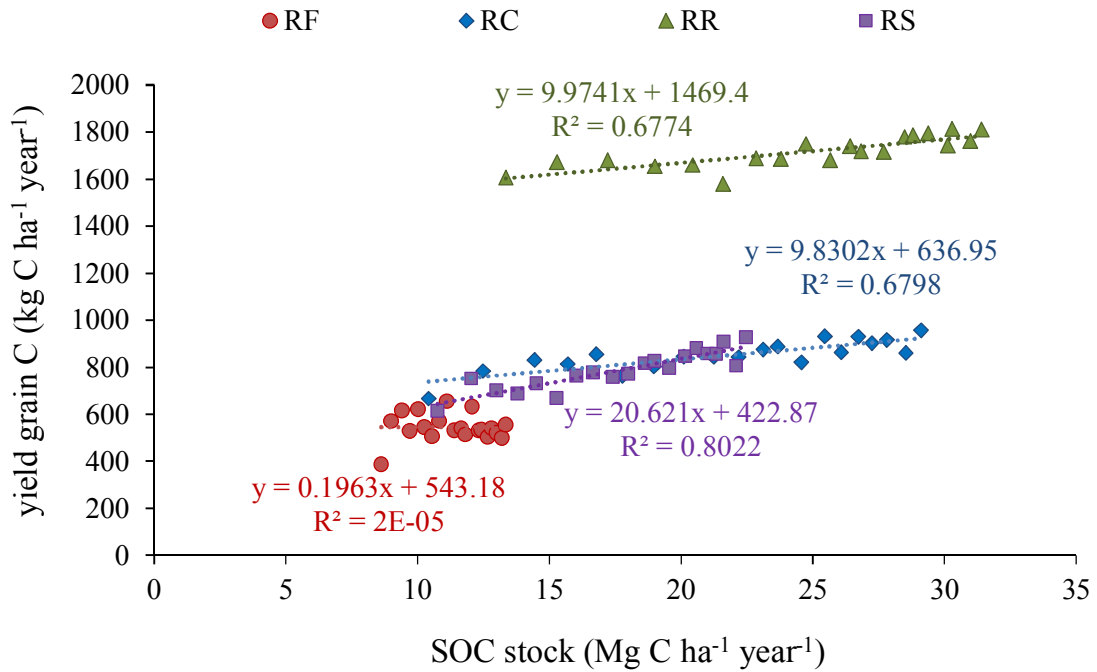


Figure 5.14 Relationship between annual SOC stock and yield grain C (20 years)

## 5.4 Discussion

### 5.4.1 Short-term simulation by DNDC model on GHG emissions and SOC stocks under different crop rotation systems

#### 5.4.1.1 GHG emissions

The validated results show that the DNDC model able to capture the overall trend of the daily CH<sub>4</sub> emissions in the crop rotation treatments of RF, RC and RS, but failed to capture in the double cropping of rice (RR) (Figure 5.3-5.4). The higher  $r$  and  $R^2$ , and the smaller  $E$  and RMSE analysis as observed in RF, RC and RS indicate that the DNDC model is greater prediction accuracy and useful tool for estimating CH<sub>4</sub> emissions from the different crop rotation systems. The observed values in RR cropping system found the larger CH<sub>4</sub> flux peak after two weeks of rice sowing, which model was underestimate and could not capture during this period. According to direct seeding method for rice cultivation, the field did not have flooding after sowing to ~30 days of rice growing period, but the extreme CH<sub>4</sub> flux peaks were observed (as discussed in Chapter 3). During non-flooded period at beginning of the rice field, DNDC model was low CH<sub>4</sub> fluxes calculation by ebullition or direct emission from the soil surface. The CH<sub>4</sub> fluxes results from this condition were similar to irrigated rice management under alternate wetting and drying (AWD) as found in Katayanagi *et al.* (2012).

Concerned with improving the model, Fumoto *et al.* (2008) suggested quantifies the electron donors production (H<sub>2</sub> and dissolved organic carbon (DOC)) by decomposition and rice root exudation, and simulates production of CH<sub>4</sub> and other reductive reactions based on the availability of electron donors and acceptors (NO<sub>3</sub><sup>-</sup>, Mn<sub>4</sub><sup>+</sup>, Fe<sup>3+</sup>, and SO<sub>4</sub><sup>2-</sup>). So, the checking of these free ion contents at the beginning of rice cultivation and adjust to re-calculation should be done further to improve the model.

For N<sub>2</sub>O emissions, the model was in good agreement during fallow periods and energy crop cultivation periods (Figures 5.6-5.7), but failed to capture the timing and magnitude of daily N<sub>2</sub>O emissions. The discrepancy of simulation created the low correlation coefficient ( $r = 0.05-0.09$ ,  $R^2 = 0.0028-0.0090$ ) and percentage of different (31-76%). Similar simulated results also found in Katayanagi *et al.* (2012). At the first cropping in 2010, modeled large magnitude N<sub>2</sub>O peaks was observed in RC and RS treatments, due to organic matter decomposition and N mineralization from cow manure incorporation into the field (Chapter 3, Table 3.1). Katayanagi *et al.* (2012) point out that the discrepancy may have

been the overestimation of plant growth by the model, by which the higher simulated plant growth would have resulted in higher nitrogen uptake by the plants, leaving less nitrogen available to support microbial activity in the soil and causing low N<sub>2</sub>O emissions. Moreover, the discrepancy may have been an incorrect balance between nitrification and denitrification rates in the model.

#### **5.4.1.2 SOC stock**

Simulated results from DNDC model could capture the pattern of the field observation, especially in RC and RS treatments (Figure 5.10). The closest to one of the correlation coefficient ( $r$ ), and slight of error analysis (E and RMSE) in RC and RS were confirmed that the DNDC model has pretty good prediction accuracy. Accordingly, this model is ability tool to simulate the SOC change in the short term as affected by the different crop rotated with rice field.

Even though, the DNDC had simulated SOC stock in rotation of RC and RC well, the overestimation was also observed in the continuous rice (RR). This result may explain by the crop dataset input (Table 5.2). The continuous lowland rice sequence influences the carbon sequestration in soil, due to continuous incorporation of rice residue and the slow decomposition during rice growing season (Watanabe, 1984; Fores *et al.*, 1998).

Furthermore, the loss in SOC occurred in the RF treatment because of the high temperature during the fallow period, resulting in high decomposition rates of organic matter in the dry season. This results in agreement with Babu *et al.* (2006). Mu *et al.* (2014) pointed that microorganisms may become more active under the constantly increased temperatures, which would accelerate the decomposition of soil organic matter.

### **5.4.2 Long-term simulation by DNDC model on GHG emissions and SOC stocks under different crop rotation systems**

#### **5.4.2.1 GHG emissions**

A 20-year simulation was conducted with the DNDC model to study the GHG emissions under different crop rotation systems. The purpose was to find suitable cropping systems that might reduce GHG emissions in the long-term. The simulation results found that the crop rotation management with corn and sweet sorghum in rice field could reduce CH<sub>4</sub> emission by 72% and 80%, respectively when compared with continuous rice cultivation (RR) (Figure 5.5). In year 2023, CH<sub>4</sub> emission in all treatments rapidly increased with increases in temperature (Figure 5.2). These results indicated that the climate change was sensitive on CH<sub>4</sub> emission. Similar result was found in Babu *et al.*, 2005. However, the

increasing rates of CH<sub>4</sub> emission per annual were low and the emissions might be stability in further 30 years.

Long-term simulation of annual N<sub>2</sub>O emissions (Figure 5.9) had similar patterns to CH<sub>4</sub> emissions but differed in quantity among the four treatments. Because of CH<sub>4</sub> was significantly emitted during rice growing season, while N<sub>2</sub>O emitted during fallow land and upland crop season (Nishimura *et al.*, 2008). N<sub>2</sub>O emissions were also rapidly increased after 10-years simulation, might be affected by the climate variations as similar effect to CH<sub>4</sub> emission. The N<sub>2</sub>O emissions from the rotation with corn (RC) and sweet sorghum (RS) were four and two times higher than that in double cropping of rice (RR), respectively. In particular options to reduce N<sub>2</sub>O emission in long period from energy crops rotation management should be decreased the fertilizer application.

The relationship between annual CH<sub>4</sub> emissions and yield grain C in the 20-year simulations (Figure 5.6) showed that the crop rotations with corn and sweet sorghum not only increased grain yield, but also reduced CH<sub>4</sub> emissions in the long-term when compared with continuous rice cultivation. While, an increased yield grain C significant correlated with in increased N<sub>2</sub>O emission in long term simulation (Figure 5.10). That is the increasing of yield grain C in the double cropping systems i.e. rice-rice, corn-rice and sweet sorghum-rice were affected by fertilizer application. The application of N fertilizer significantly affected in the upland crops due to the nitrification process under aerobic and anaerobic condition during crop growing season.

#### **5.4.2.2 SOC stock**

In long-term predictions, SOC stocks in all crop rotation systems constantly increased with the simulation year (Figure 5.13). The soil organic carbon sequestration in the rotation of rice-rice (RR) and energy crop- rice (RC and RS) was significant higher than single cropping of rice (RF), there was similar to the trend of the short term simulation and the field observation (Figure 5.12). Therefore, long-term crop rotation viewpoint, energy crop rotated with rain-fed rice have been better than a single cropping of rain-fed rice (RF) to achieve soil carbon sequestration goal.

The SOC stock is reasonably highest in RR because the double rice residue with higher C/N ratio (Table 5.1), relatively slower decomposed under anaerobic condition due to high organic carbon accumulation. Although, RC and RS were also double crop residues from energy and rice crop but the C/N ratios of corn and sweet sorghum residues were lower, lead to higher decomposition rates and enhance soil carbon loss under aerobic

condition. Liping and Erda, (2001) studied the land use change from upland to rice soil in past 600 years in China, and found that the rice soils accumulated more organic carbon than the upland soil by 12-58%. The conversion of upland soils to rice soils was increased organic carbon stored by 120.8-584.0 Tg in 0-100 soil depth. Kukal *et al.* (2009) also studied long term (32 years) of C sequestration in rice-wheat and maize-wheat system in Panjap (India), they found that SOC content in the rotation of rice-wheat was 21-24 % higher than maize-wheat.

In the long-term simulation, an increased yield grain C also significantly correlated with SOC stock in RR, RC and RS treatments (Figure 5.14). So, the rotation of energy crops in rice field is not only enhanced SOC stock but also significant improved crop productivity than that in conventional single rice cultivation (RF).

#### **5.4.3 Advantages and limitation of the model**

The tested short-term (two and a half years) simulations of CH<sub>4</sub> and N<sub>2</sub>O emissions and SOC stocks seemed to be dependent on the different crop cultivations, field preparation practices, fraction of crop residue returned to the soil, and their C/N ratios. In term of the rice cultivation in Thailand, the specific of field preparation and irrigation management was strongly effect to high CH<sub>4</sub> emission at the beginning of rice growing season, which the DNDC model (version 9.3) could not capture in this period. Conversely, The DNDC model was good agreement in the crop rotation treatments of RF, RC and RS for predict CH<sub>4</sub> emissions. The DNDC model was also good prediction accuracy for SOC stock, especially in the rotation of RC and RS treatments.

### **5.5 Summary and Conclusion**

In short-term simulations, the measured emissions of CH<sub>4</sub>, especially in RR, RC and RS, were well described by the DNDC model. The DNDC model captured the overall trends of the daily CH<sub>4</sub> emissions in the crop rotation treatments of RF, RC and RS well, but was unsuccessful in capturing the beginning of rice growing season in RR treatments. These results indicate that the DNDC model is a useful tool for estimating CH<sub>4</sub> emissions from the rotation systems between rice and upland crops. For N<sub>2</sub>O emissions, the model was good agreement during fallow period and energy crop cultivation period, but failed to capture the timing and magnitude of daily N<sub>2</sub>O emissions. In the long term simulation, CH<sub>4</sub> emissions from the energy crop rotations were reduced 72% in rotation with corn (RC) and 80% in

rotation with sweet sorghum (RS) when compared with continuous rice cultivation (RR). The N<sub>2</sub>O emissions from the rotation with corn (RC) and sweet sorghum (RS) were four and two times higher than double cropping of rice (RR), respectively.

Simulated results of SOC stock in the short term could capture the patterns of the field observation, especially in RC and RS treatments, which confirmed the model talent to simulate the effects of different energy crop rotations in rice field. In this case study, the SOC validation in the short term (three years) is not enough for confirm the ability of the model in order to predict the changing of SOC stock in longer period. However, this long term prediction able to see the feasibility of SOC stock under the different crop rotation systems. In order to SOC sequestration in long term, the rotation of rice-rice (RR) and energy crop- rice (RC and RS) was significant higher than that in single cropping of rice (RF).

Overall results suggest that the cropping management, such as the crop type, the amount and fraction of crop residue, may dominate the accuracy of DNDC performances. The model also could simulate the effects of weather and crop management practices, such as water and fertilization management, on N<sub>2</sub>O and CH<sub>4</sub> emissions. In the case of SOC stock, the validation of simulation results should be observed the SOC stock from the experimental field more than three years. That is well in validation, leading to high ability and accuracy of the DNDC model.

According to the results of this study, to decrease GHG emissions, the current method of agricultural management should be improved, such as increasing suitable time for crop residue decomposition before rice cultivation, decrease flooding period during rice growing season and decrease the amount of N fertilizer application in both rice and energy crop seasons. In order to increasing of SOC stock, crop residue return to soil should be increase and using the crop rotation management should be used, such as lowland rice rotated with upland crops.

## **CHAPTER 6**

### **OVERALL CONCLUSION**

Global rice production area was approximately 165 million ha, which 52 million ha devoted to rain-fed lowlands rice. Thailand is an agricultural country and rice is the most important crop. Approximately 60% of the rice cultivation area is accounted to be used for the major rice, which was cultivated under rain-fed (~ four months) and will be left as the fallow land in dry season (~ eight months). Many rain-fed rice areas in Thailand have low soil fertility and poor management during fallow period, its often lost opportunity to double crop cultivation in one year. This conventional practice may cause poor soil properties and low rice production.

Crop rotation in rice field can improve utilization of agricultural land, but different crop systems and managements have effects on GHG emissions. Commonly known that rice cultivation is one of the most important sources for atmospheric GHG emissions as CH<sub>4</sub> and N<sub>2</sub>O. Rice cultivation emitted 493-723 Mt CO<sub>2</sub>eq year<sup>-1</sup>. The improving of SOC is the important issues that affect agricultural production, soil nutrient availability, soil stability and GHG emission. It is fortunate that Thailand is located in the tropical zone, where is suitable for many energy crops cultivation. It can be used for rotation with main rice and production of bio-fuels which can well substitute the fossil-based oil.

Therefore, the overall goal of this study is to find a suitable crop rotation system in agricultural fields in order to mitigating GHG emissions, improving SOC sequestration and increasing agricultural crop production, as well as to reduce global warming and increase utilization of agricultural land.

#### **6.1 Crop rotation systems in rice fields for mitigating GHG emissions and crop production**

The selected energy crop rotations (corn and sweet sorghum) in rain-fed rice field reduced 78-84% of CH<sub>4</sub> reduction (Chapter 3, Table 3.3). In addition of re-cultivation on abandoned land by energy crop rotation in a rain-fed rice field leads to high N<sub>2</sub>O emissions, and the equivalent CO<sub>2</sub> emissions are low when compared with those of the rice-rice cropping system. The equivalent CO<sub>2</sub> emissions from CH<sub>4</sub> in the double cropping of rice (RR) were significantly higher than in energy crop rotation (RC and RS) and fallow (RF),

but the equivalent CO<sub>2</sub> emissions from N<sub>2</sub>O were less in RR. The energy crops and fallow land (RF) rotated with rain-fed rice reduced GHG emissions by 59-82%.

The rain-fed rice grain yields in the rotation with corn (RC) and sweet sorghum (RS) were significantly higher than single rice (RF) and double cropping of rice (RR). These results indicated that the rotation of energy crops (both corn and sweet sorghum) had significantly improved rain-fed rice yield after consecutive cultivation, which is required to feed the population, while decreasing the ratio of GHG emissions per rice grain yield.

These findings indicate that the energy crop rotation management is a suitable cropping option not only for greenhouse gas mitigation and stabilizing the rice production, but also increasing economic and social benefits through more opportunity for possible incomes.

## **6.2 Crop rotation systems in rice fields for improving soil properties, soil carbon budgets and soil organic carbon stocks**

The soil physical properties and soil nutrient elements varied with different crop seasons. The soil BD was generally high after the rice cropping. The initial soil (abandoned field) was slightly acidic (pH 5.8-6.2) and after crop rotation with rice, the soils shift towards a more neutral pH (6.6-7.1). The amounts of SOM, total N, available P and available K from this study were low to very low ranges of plants benefits. SCBs were strongly affected by the crop residue management and cultivation practices. The SOC stocks were maintained by the RR, RC and RS treatments, but significantly decreased by the RF treatment in the second year. The relations between carbon input to the soil and SOC stock suggest that in all treatments, the carbon input improves the SOC stock. Note that the experiment was done only two years. The results indicated that the other crop rotations in rain-fed rice field able to maintain SOC stock in short-term.

These finding indicate that energy crop rotation with rain-fed rice gradually improved soil fertility, and maintained soil organic carbon stock than that in conventional rice cultivation system (RF). Therefore, the rotation of rice with energy crops, especially corn-rice rotation system is the suitable crop management option in order to sustainable agricultural land use and should be suggest and implement for Thai farming.

### **6.3 Possible application of DNDC model for short-term and long-term variations of GHG emissions and SOC stocks**

In short-term simulations, the DNDC model is a useful tool for estimating CH<sub>4</sub> emissions from the energy crop rotation systems. However, this model cannot define CH<sub>4</sub> emissions at the beginning of the rice growing season in a continuous rice field. The simulated N<sub>2</sub>O emissions was good agreement during fallow period and energy crop cultivation period, but failed to capture the timing and magnitude of daily N<sub>2</sub>O emissions. Simulated results of SOC stock in the short term could capture the patterns of the field observation, especially in RC and RS treatments, which confirmed that the model talent to simulate the effects of different energy crop rotations in rice field. In long term simulation, an annual CH<sub>4</sub> and N<sub>2</sub>O emissions and SOC stock in all treatments gradually increased. The emissions of CH<sub>4</sub> and N<sub>2</sub>O were affected by the climate change.

The DNDC model is a complex process-based model that required more details of climate conditions, soil properties and cultivation management for estimating CH<sub>4</sub> and N<sub>2</sub>O emissions and soil organic carbon storage. Since Thailand is located in the tropical zone, the variation of climate is an important influencing factor on the rate of decomposition and CH<sub>4</sub> and N<sub>2</sub>O emissions. The simulated results from DNDC model application under different crop rotation systems indicated that the crop management practices, such as the land type for each crop cultivation, the amount of crop residue returned, and fraction of crop residue are the important factors, which is dominated the accuracy of DNDC performances. The model also simulate the effects of weather and crop management practices, such as water and fertilization management, on N<sub>2</sub>O and CH<sub>4</sub> emissions.

The accuracy of the simulation of CH<sub>4</sub> emissions and SOC storage from energy crop rotations in rain-fed rice fields was sufficiently good for practical use of the model in both short-term and long-term predictions.

### **6.4 Conclusion**

This study focused on the cultivation of the main food crop (rice) and the energy crops at the same place in order to reducing GHG emissions, increasing soil fertility and soil organic carbon stock, and enhancing agricultural crop production.

The experiments designed with four different crop rotation treatments in a rice field where the conventional practice is normally to grow a single rain-fed rice crop each year (RF) have shown that rotating with irrigated rice (RR) as a conventional cultivation practice under irrigated area, as well as with selected energy crops (RC and RS) in the dry season can significantly reduce GHG emissions, increase soil carbon sequestration, and stabilize the rain-fed rice yield in both short term and long term estimation.

For these reasons we recommend the growing of energy crops, i.e. corn or sweet sorghum, rather than an extra crop of rice by irrigation, especially as double-cropping of rice each year will reduce soil quality and rice yields in the long term. This implementation is not only beneficial for food production but also benefit for feedstock production in ethanol production as the one of renewable energy. In addition, the energy crops provide feedstock for biofuel production without competing for land that would otherwise be used for food production.

The implementation of energy crop rotation management in rain-fed rice fields is a good choice for Thai farming in terms of reduced GHG emissions, maintained soil organic carbon, increases farmer income by increased crop yields, saving water in the crop cultivation, and enhanced agricultural land use. However, the limitations in this management for Thai farming system include water supply, soil quality, climate effects, crop marketing and competition between food and energy crops, especially water requirements for the crop cultivation. This experiment showed that water supply is the important issue in non-irrigation area, as shown the lack of yields of corn and irrigated rice in the first crop experiment. In order to achieve the annual benefit of rotation crop cultivation, water container or water sources such as pond and ground water need to be secured before crop cultivation.

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