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Practices for Reducing Greenhouse Gas Emissions from Rice Production in Northeast Thailand

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Abstract: Land management practices for rice productivity and carbon storage have been a key focus of research leading to opportunities for substantial greenhouse gas (GHG) mitigation. The effects of land management practices on global warming potential (GWP) and greenhouse gas intensity (GHGI) from rice production within the farm gate were investigated. For the 13 study sites, soil samples were collected by the Land Development Department in 2004. In 2014, at these same sites, soil samples were collected again to estimate the soil organic carbon sequestration rate (SOCSR) from 2004 to 2014. Surveys were conducted at each sampling site to record the rice yield and management practices. The carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions, Net GWP, and GHGI associated with the management practices were calculated. Mean rice yield and SOCSR were 3307 kg·ha^{-1}·year^{-1} and 1173 kg·C·ha^{-1}·year^{-1}, respectively. The net GWP varied across sites, from 819 to 5170 kg·CO_2eq·ha^{-1}·year^{-1}, with an average value of 3090 kg·CO_2eq·ha^{-1}·year^{-1}. GHGI ranged from 0.31 to 1.68 kg·CO_2eq·kg^{-1} yield, with an average value of 0.97 kg·CO_2eq·kg^{-1} yield. Our findings revealed that the amount of potassium (potash, K_2O) fertilizer application rate is the most significant factor explaining rice yield and SOCSR. The burning of rice residues in the field was the main factor determining GHGI in this area. An effective way to reduce GHG emissions and contribute to sustainable rice production for food security with low GHGI and high productivity is avoiding the burning of rice residues.

Keywords: land management practices; rice field; net global warming potential; greenhouse gas intensity; Northeast Thailand

1. Introduction

Rice fields have been a concern of scientists worldwide because they emit the three most potent and long-lived greenhouse gases (GHGs), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [1,2], because of their positive increases in radiative forcing and their contribution to global warming [3]. Flooded rice fields emit CH_4 due to a methanogenesis process that occurs in anaerobic conditions, during which organic matter (OM) undergoes decomposition [4]. Factors affecting CH_4 emissions, such as weather conditions [5], the water regime [6], soil properties [7], land practices, i.e., irrigation [8], organic amendments [9], fertilization [10], and rice varieties [11], have been considered. Most N_2O emissions occur from nitrogen (N) fertilizer application [12], for which the N application rate is the main driver of N_2O production for either wet or dry soil [13]. However, rain-fed areas are more comparable and have stronger N_2O emissions from rice fields than other areas [14] because of changes in soil oxygen status, soil redox potential, soil moisture, and soil temperature [15]. With regard to CO_2 emissions, the main sources are the activities of farmers on their land, particularly when crop residues are burned and machines use energy either for cropping operations (i.e., tillage, harvesting, and so on) or stationary operations (i.e., water pumping, land preparation, and application of insecticides and herbicides) [16]. Furthermore, the burning of crop residues not only emits CO_2 but is also a major source of gaseous pollutants such as carbon monoxide (CO), CH_4, N_2O, and hydrocarbons in the troposphere [17]. However, soils have the potential to mitigate increasing CO_2 concentrations through carbon sequestration, with the maximum potential global sequestration varying from 0.45 to 0.9 $Pg{\cdot}C{\cdot}year^{-1}$ [18]. Therefore, understanding the effects of management practices on GHG emissions and soil organic carbon (SOC) is necessary to improve management practices to reduce GHG emissions from rice fields.

Thailand's rice production area is 13.28 million ha, which is approximately 55.6% of the country's total agricultural area [19]. Geographically, Thailand is divided into four main regions, the North, Northeast, Central, and South. Rice is grown throughout the country, but the Northeast, North, and Central are the most important rice-growing regions with 49.1%, 25.4%, and 22.3%, respectively, of the country's total rice growing area. The Northeast has a majority of the rain-fed lowland areas with around 4.8 million ha [20] and shallow drought-prone areas [21]. Traditional rice varieties, particularly Jasmine rice or Khao Dawk Mali 105 (KDML 105), are grown in the Northeast. Although the rice quality is high, the rice yield is low, and the farmers in this area are the poorest compared to the other regions [19]. To obtain sustainable management of the sandy soil in this area, it is necessary to understand the land management practices, which include the farmers' actual activities and practices, and determine the appropriate practices in terms of the soil characteristics and farmers' capability. By understanding these elements, the pros and cons of each land management practice in relation to GHG emissions, SOC, and rice yield can be thoroughly estimated. To estimate the overall effects of rice fields, the concept of net global warming potential (GWP) was proposed based on the radiative properties of CO_2, CH_4, and N_2O emissions and SOC variations, expressed as $kg{\cdot}CO_2eq{\cdot}ha^{-1}{\cdot}year^{-1}$ [22]. Moreover, the agricultural practices can be related to GWP by estimating net GWP per ton of crop yield, which is referred to as greenhouse gas intensity (GHGI) [23]. Net GWP reflects the balance between SOC storage and GHG emissions. A negative net GWP value means that the system is taking GHGs out of the atmosphere, whereas a positive net GWP value means that GHGs are being added to the atmosphere and net GWP increases [24]. In addition, a positive GHGI value indicates a net source of GHGs per kilogram of yield per year, whereas a negative value indicates a net sink of GHGs in soil [25]. No studies to date have estimated net GWP and GHGI in this area under different land management practices, including irrigated versus rain-fed fields. The aim of this study was to estimate the effect of land management practices on net GWP and GHGI.

2. Materials and Methods

2.1. Description of the Study Area

The study area is situated in Thung Kula subdistrict, Suwannaphum district, Roi-Et province, Thailand (15°28′ N, 103°48′ E) and covers 59.45 ha, 22. 29 ha of which was irrigated and 37.16 ha was rain-fed. Roi Et soils are derived from washed deposits of sandstone and occur on the lower parts of peneplains. The elevation ranges from 100 to 200 m above sea level. This area has a tropical monsoon climate (Köppen 'Aw'). The average annual precipitation in 2014 ranged from 800 to 2900 mm, and the mean annual air temperature ranged from 26 to 28 °C. The major soil type in Roi-Et Province is Ultisol with more than 60% sand content; low SOC, ranging from 0.40% to 1.29%; and medium acid surface soil of pH 5.0–6.0 [26]. In general, the soils are deep, and are characterized by different colors; however, the dominant colors are a grayish-brown or light brown sandy loam A horizon overlying a light brown grading to pinkish-gray sandy clay loam or loam kandic B horizon, which, in turn, overlies a light gray or whitish clay loam or clay C horizon. The soils are mottled throughout the profile, with strong brown or yellowish brown or dark brown and some yellowish red or red mottles being common in the subsoil. The reaction is medium acidic over strong to very strongly acidic [27].

Rice in the study area refers to the major rice crop, which is grown during the rainy season between July and December, and the second rice crop, which is grown during the dry season between January and April of the following year [28]. Most rice fields use rain-fed cultivation, in which rice is grown only once a year because precipitation is a major limiting factor. Farmers in some irrigated areas are able to grow rice twice a year, for both major and second rice crops. Jasmine rice (*Oryza sativa*) is most commonly grown in this area. The dominant rice varieties recorded in this study were Khao Dawk Mali 105 (KDML 105), RD 6, and Suphanburi 60. KDML105 and RD 6 are strongly photoperiod sensitive and flower in late October, regardless of sowing time, whereas Suphanburi 60 is a non-photosensitive rice variety.

The main conventional management practices used in the study area are as follows. First, during the growing period, both major and second rice crops are cultivated using the broadcast method and harvested by machine. Second, for tillage management, conventional tillage to a depth of 20 to 30 cm is performed by a machine. Third, after harvesting, farmers apply one of two forms of rice straw and stubble management incorporation into the soil or burning in the field. The farmers usually burn rice residue after major rice harvesting (dry season) because of the ease and convenience of tillage to prepare for the next crop. Fourth, for water management, continuous flooding and shallow flooding are used for the irrigated and rain-fed areas, respectively. In irrigated areas, fields are inundated with 10 to 15 cm of standing water throughout the growing period and drained or naturally dried 7 to 10 days before harvesting. In rain-fed areas, the soil was temporarily flooded depending on rainfall, or water pumping when rain water was unavailable. Fifth, for manure and chemical fertilizer application, cattle manure was often added to the soil as a basal fertilizer once a year, usually after the previous crop was harvested or at the beginning of planting the next crop. The following chemical fertilizer types were found in the study area: 46-0-0, 16-16-8, 16-20-0, 0-0-60, 15-15-15, and 16-8-8.

According to the survey of soil nutrient status in Thailand from 2004–2008, soil samples of 13 sites in the study area were collected during the dry season after the rice harvest by the laboratory of the Office of Science for Land Development, Land Development Department, Ministry of Agriculture and Cooperatives, Thailand. Data from the 13 sites, nine of which were irrigated areas and four rain-fed areas, in Thung Kula subdistrict, were obtained from the soil pH, bulk density, OM, organic carbon (OC), total nitrogen, available P, available K, electrical conductivity, and lime requirement in 2004. We, therefore, estimated SOC in 2004 based on the soil bulk density, OC, and depth (30 cm) in 2004. In 2014, we again collected soil samples from the same 13 study sites to estimate the soil organic carbon sequestration rate (SOCSR) from 2004 to 2014.

2.2. Data Collection

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

2.3. Soil Sampling

Soil samples were collected during the dry season after the rice harvest (November 2014). At each site, the soil horizons from 0 to 40 cm depth were identified by considering specific physical features, namely color and texture. Three soil samples (replications) of each soil horizon were then collected. Any visible roots, stones, or organic residues were removed manually after the samples were air-dried at room temperature (31–33 °C). The samples were passed through a 2-mm sieve. The SOC content (fine fraction < 2 mm) was determined using the wet oxidation method with $K_2Cr_2O_7$ and concentrated H_2SO_4 as described by Walkley and Black [29]. Soil bulk density was taken using the soil core. After a 24 h drying period in an oven at 105 °C, the soil bulk density was determined as the dry weight per unit volume of the soil core.

2.4. Estimation of GHG Emissions

The GHG emissions were calculated within the farm gate. Therefore, the GHG emissions of raw materials production and the transportation of agricultural inputs to the farm were not included. The emission factors for the calculation of GHG emissions, which were provided by Arunrat et al., are presented in Table 1 [30].

Table 1. Emissions factors used for the calculation of GHG emissions within the farm gate (utilization phase) [30].

Activity	Emissions Factor	Unit	Source
Agriculture Input			
Diesel used (stationary combustion) for farm operation	2.7446	$kg \cdot CO_2eq \cdot L^{-1}$	[31]
Gasoline used (stationary combustion) for farm operation	2.1896	$kg \cdot CO_2eq \cdot L^{-1}$	
Diesel used (mobile combustion) for farm operation	Tractor = 3.908 Harvester = 2.645	$kg \cdot CO_2eq \cdot L^{-1}$	[32] (calculated with diesel density of 0.832 $kg \cdot L^{-1}$)
Gasoline used (mobile combustion) for farm operation	2.319	$kg \cdot CO_2eq \cdot L^{-1}$	[33]
Insecticide	5.1	$kg \cdot CO_2eq \cdot kg^{-1}$	[34]
Herbicide	6.3	$kg \cdot CO_2eq \cdot kg^{-1}$	[34]
CH_4 Emission from Rice Cultivation			
EF_c	3.12	$kg \cdot CH_4 \cdot ha^{-1} \cdot day^{-1}$	[35]
SF_w	0.52 in all systems		[31]
SF_p	*Rw* = 0.68, *Lw*, *Ld* = 1		
ROA_i	2.5	$ton \cdot ha^{-1}$	
$CFOA_i$	*Rw* = 0.29, *Lw*, *Ld* = 1		
SF_0	*Rw* = 1.4, *Lw*, *Ld* = 2.1		
Direct and Indirect N_2O Emission from Managed Soils (Chemical and Organic Fertilizer)			
EF_1	0.01	$kg \cdot N_2O\text{-}N \cdot kg^{-1}$ N input	[31]
EF_{1FR}	0.003	$kg \cdot N_2O\text{-}N \cdot kg^{-1}$ N input	
EF_2	0.01	$kg \cdot N_2O\text{-}N \cdot (kg \cdot NH_3\text{-}N + kg \cdot NO_x\text{-}N \text{ volatilized})^{-1}$	
EF_3	0.0075	$kg \cdot N_2O\text{-}N \cdot kg$ leaching per runoff	
$Frac_{GASF}$	0.1	$kg \cdot NH_3\text{-}N \cdot + NO_x\text{-}N \cdot kg^{-1}$ N applied	
$Frac_{LEACH\text{-}(H)}$	0.3	$kg \cdot N \cdot kg^{-1}$ N additions	

Table 1. *Cont.*

Activity	Emissions Factor	Unit	Source
Burning Crop Residue			
CH_4	2.7	g·kg^{-1} dry matter burned	[31]
N_2O	0.07	g·kg^{-1} dry matter burned	
Dry matter fraction	1		
Fraction burned	0.29		
Fraction oxidized	0.9		
Rice residue to crop ratio	Irrigated areas: major rice = 1.06; second rice = 0.65		[36]
	Rain-fed areas: major rice and second rice = 0.55		

2.4.1. CO_2 Emissions from Fossil Fuel Utilization

The CO_2 emissions for the diesel and gasoline usage of stationary combustion were also taken from the IPCC [31]. The CO_2 emissions from the mobile combustion of the diesel fuel of farm tractors and harvesters were estimated from the emission factors of Maciel et al. [32], and CO_2 emissions from gasoline fuel were estimated from the EPA [33]. Figures for insecticides and herbicides were provided by the emissions factors from Lal [34]. The equations are detailed as following details:

(1) Diesel fuel

$$CO_2 \text{ emissions from diesel fuel utilization} = \text{Total amount of diesel fuel} \times \text{emissions factor of diesel fuel combustion.} \quad (1)$$

(2) Gasoline fuel

$$CO_2 \text{ emissions from gasoline fuel utilization} = \text{Total amount of gasoline fuel} \times \text{emissions factor of gasoline fuel combustion.} \quad (2)$$

2.4.2. CO_2 Emissions from Insecticide and Herbicide Utilization

The calculation for CO_2 emissions from insecticide and herbicide utilization was calculated as follows:

$$CO_2 \text{ emissions from insecticide and herbicide utilization} = \text{Total amount of insecticide and herbicide application} \times \text{emissions factor of insecticide and herbicide utilization.} \quad (3)$$

2.4.3. CH_4 Emissions from Rice Production

Field CH_4 emissions from rice cultivation were used as the model for the calculations according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [31]. The baseline emission factor was taken from Yan et al. [35], who adjusted the region-specific emission factors for rice fields in east, southeast, and south Asian countries, and all scaling factors used were from the IPCC [31].

The basic equation to estimate CH_4 emissions from rice cultivation is based on the IPCC Guidelines [31] (Tier 2) (Equation (4)). CH_4 emissions were estimated by multiplying the daily emissions factor by the cultivation period of rice:

$$CH_4 = EF \times t, \quad (4)$$

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

Emissions from each different region were calculated by multiplying a baseline default emissions factor by the various scaling factors, as shown in Equation (5):

$$EF = \left(EF_c \times SF_w \times SF_p \times SF_o \times SF_{s,r}\right), \quad (5)$$

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

Meanwhile, Equation (6) and the default conversion factor for farmyard manure presented an approach to vary the scaling factor according to the amount of farmyard manure applied:

$$SF_0 = (1 + \sum_i ROA_i \times CFOA_i)^{0.59}, \quad (6)$$

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

2.4.4. N_2O Emissions from Managed Soils

The direct and indirect N_2O emissions were estimated using the methodology proposed by the IPCC [31].

The methodology for estimating direct N_2O emissions from chemical fertilizer application is given by IPCC Guidelines [31] (Tier 1) as follows:

$$\text{Direct N}_2\text{O emissions} = [F_{SN} \times EF_1 + (F_{SN})_{FR} \times EF_{1FR}] \times 44/28, \quad (7)$$

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

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

$$\text{Indirect N}_2\text{O emissions} = [F_{SN} \times Frac_{GASF} \times EF_2 + F_{SN} \times Frac_{LEACH\text{-}(H)} \times EF_3] \times 44/28, \quad (8)$$

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

2.4.5. GHG Emissions from Field Burning

The calculation for GHG emissions from field burning was calculated as follows [37]:

$$\text{The quantity of rice straw} = \text{Rice production} \times \text{Residue to crop ratio} \quad (9)$$

$$\text{Amount of burned residues} = \text{Quantity of rice straw} \times \text{fraction of area burned} \times \text{dry matter fraction} \times \text{fraction burned} \times \text{fraction oxidized} \quad (10)$$

$$\text{CH}_4 \text{ emissions from field burning} = \text{Amount of burned residues} \times \text{CH}_4 \text{ emissions factor} \quad (11)$$

$$N_2O \text{ emissions from field burning} = \text{Amount of burned residues} \times N_2O \text{ emissions factor.} \quad (12)$$

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

2.5. SOC Calculation

SOC stock was calculated by:

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

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

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

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

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

2.6. Net Global Warming Potential

The GWP based on the CH_4, CO_2, and N_2O emissions was used to account for the climatic impact on rice yield under different land management practices. To assess the combined GWP, CH_4 and N_2O were calculated as CO_2 equivalents over a 100-year time scale using a radiative forcing potential relative to CO_2 of 28 for CH_4 and 265 for N_2O [38]. The net GWP of a rice field equals the total CO_2 emissions equivalents minus the SOCSR in the rice field [39,40]:

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

2.7. Greenhouse Gas Intensity

The GHGI is calculated as a ratio of net GWP and rice yield, as described in Shang et al. [25]:

$$GHGI = \text{net } GWP/\text{rice yield.} \quad (16)$$

2.8. Statistical Analysis

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

3. Results

3.1. Pertinent Management Practices, Rice Yield, and SOC

There were no significant differences in the manure and fertilizer application rates, the amount of burned rice residues, rice yield, and SOC between irrigated and rain-fed areas (Table 2). The manure application rate varied across sites, from 0 to 4830 $kg \cdot ha^{-1} \cdot year^{-1}$, with averages of 2864 and

1888 kg·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively. The N fertilizer application rate ranged from 38 to 98 kg·ha^{-1}·year^{-1} across sites, with averages of 72 and 56 kg·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively. The P_2O_5 and K_2O application rate ranged from 14 to 46 and 6 to 46 kg·ha^{-1}·year^{-1} across sites for irrigated and rain-fed areas, respectively. The average P_2O_5 and K_2O application rates were 27 and 22 kg·ha^{-1}·year^{-1} for irrigated areas and 26 and 15 kg·ha^{-1}·year^{-1} for rain-fed areas. Meanwhile, the amount of burned rice residue was also variable, ranging from 0 to 593 kg·ha^{-1}·year^{-1}, with averages of 263 and 148 kg·ha^{-1}·year^{-1} for irrigated and rain-fed areas, respectively.

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

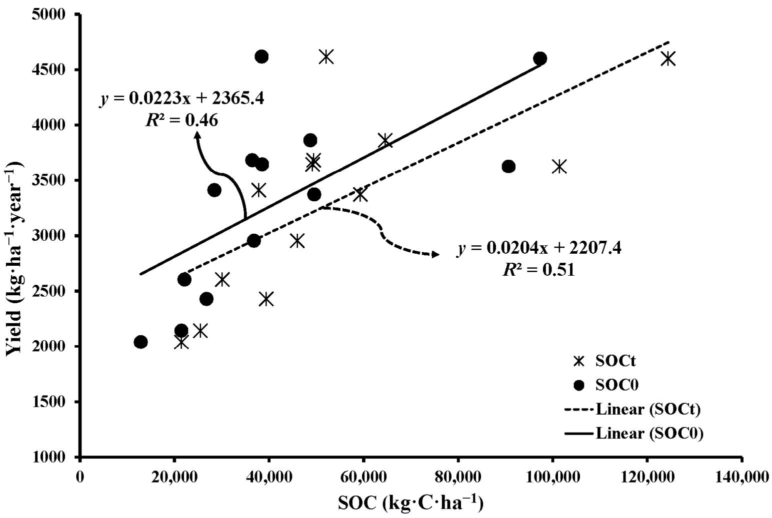

Figure 1. Relationship between rice yield and SOC_t and SOC_0 for all sites.

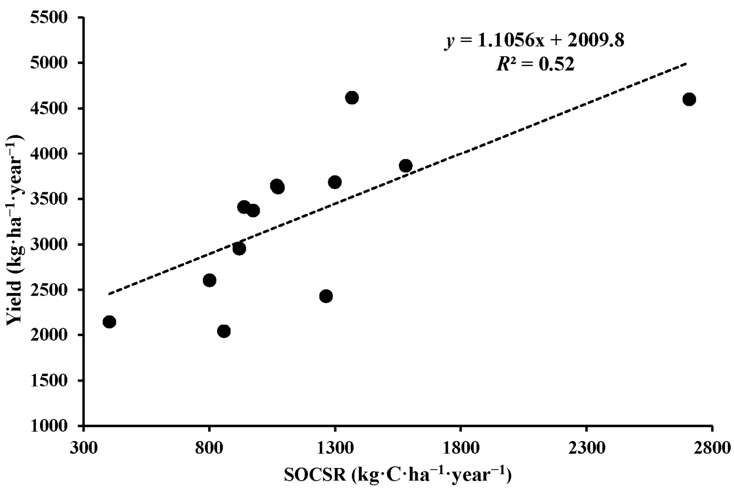

Figure 2. Relationship between rice yield and SOCSR for all sites.

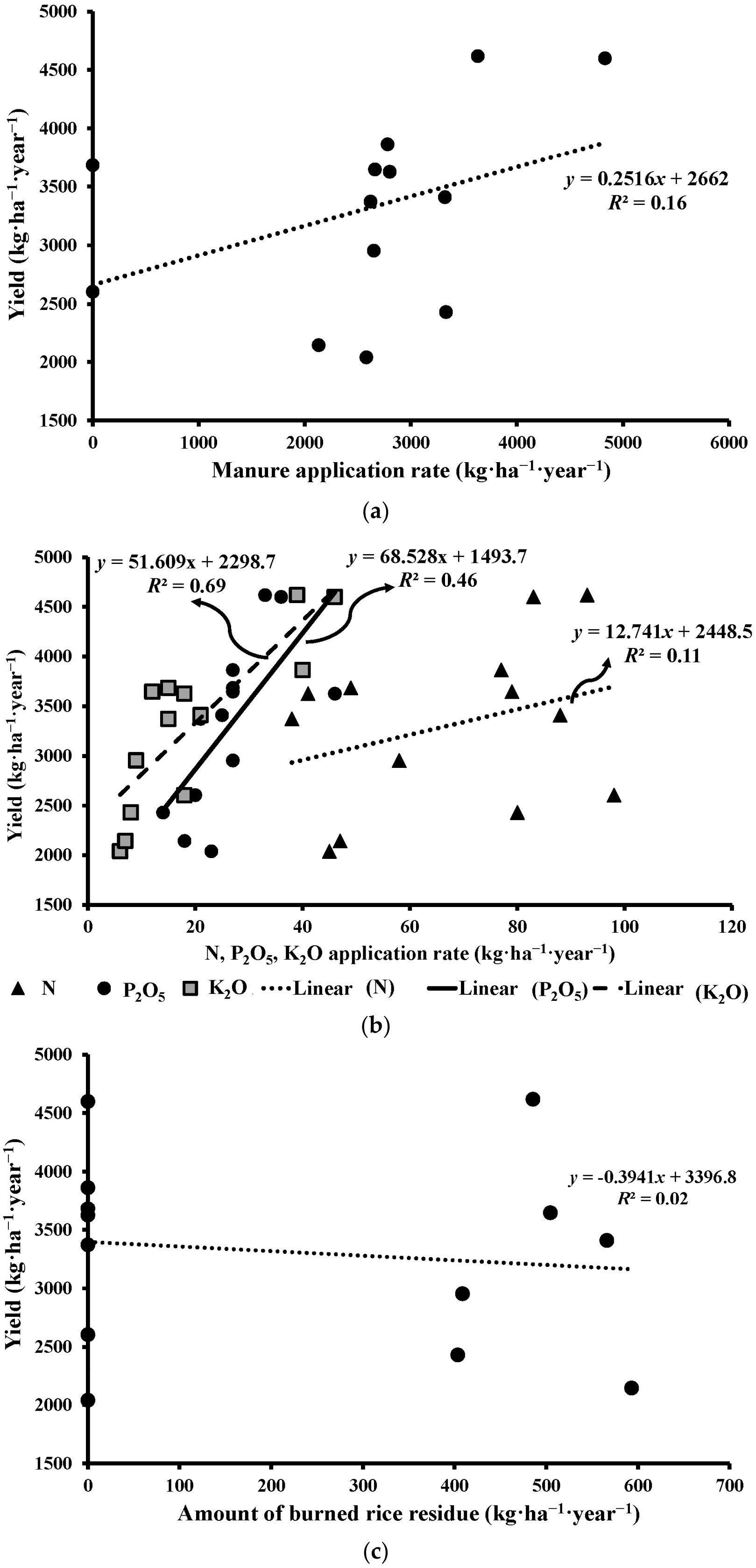

Figure 3. Relationship between pertinent practices and rice yield: (**a**) manure application; (**b**) fertilizer application; and (**c**) amount of burned rice residue.

Table 2. Pertinent management practices, rice yield, and SOCSR (mean ± standard deviation).

Site No.	Manure Application Rate ($kg \cdot ha^{-1} \cdot year^{-1}$)	Fertilizer Application Rate ($kg \cdot ha^{-1} \cdot year^{-1}$)			Burned Rice Residue (kg $\cdot ha^{-1} \cdot year^{-1}$)	Rice Yield ($kg \cdot ha^{-1} \cdot year^{-1}$)	SOC_t ($kg \cdot C \cdot ha^{-1}$)	SOC_0 ($kg \cdot C \cdot ha^{-1}$)	SOCSR ($kg \cdot C \cdot ha^{-1} \cdot year^{-1}$)
		N	P_2O_5	K_2O					
I1	3320	88	25	21	566	3410	37,810	28,430	938
I2	4830	83	36	46	0	4600	124,400	97,320	2708
I3	2780	77	27	40	0	3864	64,540	48,730	1581
I4	0	49	27	15	0	3684	49,430	36,440	1299
I5	3630	93	33	39	485	4618	52,100	38,430	1367
I6	3330	80	14	8	403	2430	39,400	26,760	1264
I7	2660	79	27	12	504	3646	49,180	38,500	1068
I8	2580	45	23	6	0	2040	21,430	12,850	858
I9	2650	58	27	9	409	2954	45,960	36,770	919
Average	2864 ± 1287	72 ± 17	27 ± 6	22 ± 16	263 ± 254	3472 ± 882	53,806 ± 28,973	40,470 ± 23,542	1334 ± 568
R1	2800	41	46	18	0	3626	101,390	90,660	1073
R2	2620	38	21	15	0	3372	59,290	49,550	974
R3	2130	47	18	7	593	2144	25,460	21,430	403
R4	0	98	20	18	0	2604	30,100	22,090	801
Average	1888 ± 1290	56 ± 28	26 ± 13	15 ± 5	148 ± 297	2937 ± 684	54,060 ± 34,926	45,933 ± 32,570	813 ± 295
p-value	0.233	0.217	0.954	0.238	0.838	0.308	0.989	0.736	0.116
Overall	2564 ± 1319	67 ± 22	26 ± 8	20 ± 14	228 ± 261	3307 ± 838	53,884 ± 29,404	42,151 ± 25,330	1173 ± 547

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

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

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

3.2. CO_2 Emissions

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

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

3.3. N_2O Emissions

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

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

Table 4. GHG emissions within the farm gate in each activity (mean ± standard deviation).

Site No.	CO_2 Emissions (kg·CO_2eq·ha^{-1}·year^{-1})			N_2O Emissions (kg·CO_2eq·ha^{-1}·year^{-1})		CH_4 Emissions (kg·CO_2eq·ha^{-1}·year^{-1})	
	Diesel Fuel	**Gasoline Fuel**	**Insecticide and Herbicide**	**Chemical Fertilizer**	**Burning Rice Residue**	**Rice Cultivation**	**Burning Rice Residue**
I1	151	28	48	487	10	5282	43
I2	188	14	73	459	0	5418	0
I3	172	23	61	423	0	4776	0
I4	166	10	67	272	0	2404	0
I5	127	19	55	511	9	4849	37
I6	135	30	41	443	7	3616	30
I7	129	65	40	438	9	5518	38
I8	159	28	38	249	0	3805	0
I9	138	49	45	399	8	3567	31
Average	152 ± 21	30 ± 17	52 ± 13	409 ± 91	5 ± 5	4359 ± 1063	20 ± 19
R1	211	51	39	227	0	2292	0
R2	206	28	52	211	0	2153	0
R3	142	73	37	404	11	2381	45
R4	193	50	42	541	0	794	0
Average	188 ± 32	51 ± 18	43 ± 7	346 ± 157	3 ± 6	1905 ± 747	11 ± 23
p-value	0.031	0.074	0.191	0.370	0.502	0.002	0.491
Overall	163 ± 29	36 ± 20	49 ± 12	390 ± 112	4 ± 5	3604 ± 1511	17 ± 20

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

3.4. CH_4 Emissions

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

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

3.5. SOCSR

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

3.6. Net GWP and GHGI

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

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

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

Table 5. CO_2, N_2O, and CH_4 emissions, and SOCSR, net GWP, and GHGI at all sites (mean ± standard deviation).

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

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

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

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

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

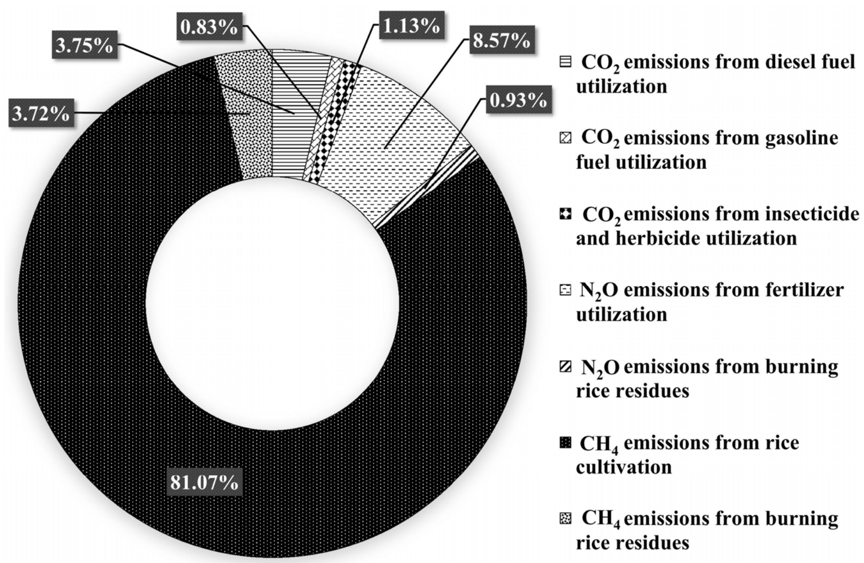

Figure 4. The contribution of GHG emission sources in each activity.

4. Discussion

4.1. Rice Yield and SOC under Different Management Practices

Proper management practices can increase SOC sequestration through increasing OM inputs to the soil. Soil organic material can be mineralized towards releasing the nutrient, which subsequently can be taken up by crops to increase crop yields. Therefore, the mineralization of soil organic matter (SOM) is a vital parameter to enhance crop yields. This is consistent with our result that rice yield had a highly positive correlation with SOC (Figure 1) and SOCSR (Figure 2). Liang et al. [41] indicated that increasing the amount of SOC could be accomplished by regular manure application with a return of more crop residues, which subsequently can lead to higher crop production. In arable land cropping systems, increasing the amount of OM in soil not only increases SOM, but also reduces net GHG emissions [42]. Moreover, studies have shown that combining both organic and chemical fertilizers can be a suitable way of enriching soil [43,44]. From this study, I2 and R1 reached the same rice yield and SOC, which was the highest overall (Table 2).

4.2. Effects of Land Management Practice on CO_2, CH_4, and N_2O Emissions

According to many previous studies, the estimation of GHG emissions from rice production varies, but they all agree that rice production is a significant contributor to overall emissions. As in flooded rice paddies generally, flooding rice fields blocks oxygen penetration into the soil, which allows bacteria capable of producing CH_4 to thrive [45]. Rice production also generates N_2O from N-fertilizer application [46]. Meanwhile, the main sources of CO_2 emissions are either cropping operations such as tillage, sowing, or harvesting, including stationary operations such as pumping water, spraying, and grain drying. The burning of rice residue is another emissions source yielding CO_2, CH_4, and N_2O [47]. This study revealed that the land management practice of highly burned rice residues generated high CH_4 and N_2O emissions, as was seen at site R3 (Table 4). In addition, more fuel consumption was found in rain-fed areas than in irrigated areas, owing to the energy needed for pumping water into rain-fed rice fields and farm operations, such as herbicide application, because the dry land would face more weeds than flooded land would. Consequently, these management practices can also produce higher amounts of CO_2eq [48].

CH_4 is produced from the decomposition of OM in anaerobic conditions by methanogens. SOM is the most common limiting factor for methanogenesis in rice fields [49]. OM arises from four main sources: animal manure, green manure, crop residues (straw, stubble, roots), and by-products of rice production (root exudates, sloughed-off root cells, and root turnover). Neue et al. [50] reported that the rice straw application of 5 Mg·ha^{-1}·year^{-1} increased CH_4 emissions 10-fold compared to the use of urea fertilizer only. Reducing the CH_4 emissions associated with water management in rice fields in which wetting and drying cycles alternate could reduce more CH_4 emissions than continuously flooded fields [9]. These results were in complete agreement with our findings that the land management practices for site I7 (Table 5) caused the highest CH_4 emissions due to the higher manure application and amount of burned rice residues than at other sites. Additionally, irrigated areas had higher CH_4 emissions than rain-fed areas, owing to the longer period of flooding in rice fields, which was similar to previous investigations by Bhattacharyya et al. [51] and Shen et al. [52]. This result was obtained from sites I1 to I9, with an average value of 4379 kg·CO_2eq·ha^{-1}·year^{-1} for irrigated areas, and sites R1 to R4, with an average value of 1916 kg·CO_2eq·ha^{-1}·year^{-1} for rain-fed areas (Table 5). However, the addition of organic material such as rice residues and manure application leads to increasing CH_4 emissions due to anaerobic decomposition [53], but it can greatly offset the mitigation benefits of soil carbon sequestration [54]. This can obviously be found at site I2, where manure is applied but no burning rice residues (Table 2), with the high SOCSR (2708 kg·CO_2eq·ha^{-1}·year^{-1}) and low GHGI (0.75 kg·CO_2eq·kg^{-1} yield) (Table 5). Based on our study, we, therefore, support the addition of manure application and returning rice residues to the soil because these practices not only gain more C storage in the soil than is released to the atmosphere but also can enhance soil fertility through the mineralization of SOM, which in turn will increase crop productivity.

Fertilizer application is important from a climate change perspective due to energy-intensive production and the positive relationship with N_2O emissions from soils [55,56]. This was consistent with our result for the land management practices at site I5 (Table 5), which generated the highest N_2O due to the high chemical fertilizer application and amount of burned rice residues.

4.3. Effects of Land Management Practice on Net GWP and GHGI

The net GWP has been illuminated to understand agriculture's impact on radiative forcing [57]. Therefore, net GWP and GHGI need to be considered when evaluating a management strategy for mitigating GHG emissions. Our study found that more burning rice residues greatly contributed to high net GWP and GHGI. Our results were consistent with Zhang et al. [58], whose study showed that a chemical fertilizer application rate of 210 kg·N·ha^{-1}·year^{-1} was the most suitable for balancing GHG emissions and rice yield in Chongming Island, Eastern China. In this study, the average GHGI was 0.97 kg·CO_2eq·kg^{-1} yield (Table 5). In Jiangsu province, China, the GHGI varied from 0.41 to 0.74 kg·CO_2eq·kg^{-1} yield under annual rice–wheat rotations with integrated soil and crop system management [59]. Qin et al. [13] studied midseason drainage and organic manure incorporation in Southeast China and found that the GHGI varied from 0.24 to 0.74 kg·CO_2eq·kg^{-1} yield, which was lower than in this study. In Thailand, the study of Yodkhum and Sampattagul [60], who applied a life cycle assessment concept and carbon footprint to determine GHG emissions of rice production in Thailand, reported that in northeast Thailand, GHG emissions of KDML 105 of NongKhai was 2.39 kg·CO_2eq·kg^{-1} yield, which was higher than in this study. Arunrat et al. [30] estimated GHG emissions based on the concept of the life cycle assessment of the greenhouse gas emissions (LCA-GHG) of products in Phichit province of Thailand. Their results revealed that GHG emissions from rice production varied from 1.81 to 2.87 kg·CO_2eq·kg^{-1} yield, and 1.72 to 2.70 kg·CO_2eq·kg^{-1} yield for irrigated and rain-fed areas, respectively, which was higher than in this study. However, the report of the Office of Agricultural Economics about the GHG emissions estimation and database developments in Thailand in 2012 using the methodology of life cycle assessment of greenhouse gas emissions of products and IPCC guideline. The GHGIs ranged from 0.67 to 3.96 kg·CO_2eq·kg^{-1} yield and averaged 2.32 kg·CO_2eq·kg^{-1} yield [36]. Taking the country's value as the baseline, the GHGI in this study was lower than the country's average. This is because the GHG emissions that occur outside the farm gate were not included in this study such as raw materials production, the transportation of agricultural inputs from manufacturing to the farm, and the transportation of rice production from the farm to the mill and storehouse. This study emphasized the balance between GHG emissions and SOC sequestration on the effect of land management practices because the SOC content at local-scale data in the estimation of GHGI, which is usually limited due to high uncertainties in the large-scale data [61]. Reasonable land management practices are the main components for mitigating GHG emissions because CO_2, CH_4, and N_2O emissions would be negated by the benefits of SOC sequestration. It is possible that the goal of reducing the net GWP and GHGI in Thailand should focus on increasing the SOC and simultaneously decreasing burning rice residues.

5. Conclusions

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

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