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Biogeochemical Cycling of Carbon and Nitrogen in Rainfed Rice Production Under Conventional and Organic Rice Farming

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ABSTRACT

Dwindling carbon (C) and nitrogen (N) levels in paddy soils decreases rice production and threaten human food security globally. The efficient maintenance of C and N fluxes in soil-rice systems is a crucial prerequisite for agricultural and environmental sustainability. Herein, we examined the C and N fluxes from 63 rainfed rice paddy fields under conventional farming (CF) and organic farming (OF) systems in Thailand. The C and N fluxes were measured based on a detailed analysis of relevant influxes (fertilizer, manure, and biomass addition) and effluxes (biomass harvest and greenhouse gas emission). The results demonstrated that the harvested grain and straw contributed to the most abundant C and N effluxes for both farming systems. The CH_4 effluxes were moderate, whereas the N_2O effluxes were meager relative to their total effluxes. Stubble incorporation and animal manure addition to soil were the most extensive C influxes. However, the primary N influxes were stubble incorporation and animal manure addition for the OF system, and chemical-N fertilizers for the CF system. Net C depletions were observed in both the CF and OF systems. However, net N was depleted and accumulated in the CF and OF systems, respectively. Straw incorporation to soils could restore the net C accumulations for the CF and OF systems and elevate the net N accumulation for both systems. This study highlighted that complete straw removal has exacerbated the C and N stock in soil-rice systems, inducing insecurity for the environment and the agricultural systems. Effective straw management is a simple approach for sustaining paddy rice production.

1. INTRODUCTION

Carbon (C) and nitrogen (N) are essential macronutrients for plants; their cycling in terrestrial ecosystems is of global importance to agriculture and the environment (Xue and An, 2018). Both elements play critical roles in plant productivity and environmental sustainability through climate change mitigation via reduced greenhouse gas emission and increased carbon sequestration (Purwanto and Alam, 2020). These elements are also primary integral components of soil organic matter (SOM) (Cheng et al., 2016; Xue and An, 2018). Globally, C distribution in agricultural soils is characterized by extensive areas of low C and N levels worldwide (Zomer et al., 2017). This indisputable evidence demonstrates that global warming threatens C sequestration in soil and terrestrial systems (Arunrat et al., 2018). Therefore, there is an urgent prerequisite to implement practical measures for enhancing C and N levels in soil-plant systems for agricultural and environmental sustainability.

Rice is a primary staple food of people worldwide, especially in Asia. Maintaining soil C and N stocks in paddy rice systems is crucial for human food security and long-term food production (Li et al., 2017; Purwanto and Alam, 2020; Zhou et al., 2020). Biogeochemical cycling of C and N fluxes in a soil-rice system involves their influxes and effluxes (Atere et al., 2017; Ge et al., 2015; Liu et al., 2019). Organic fertilization and harvested residue incorporation are primary C influxes in soil systems (Mortensen et al.,

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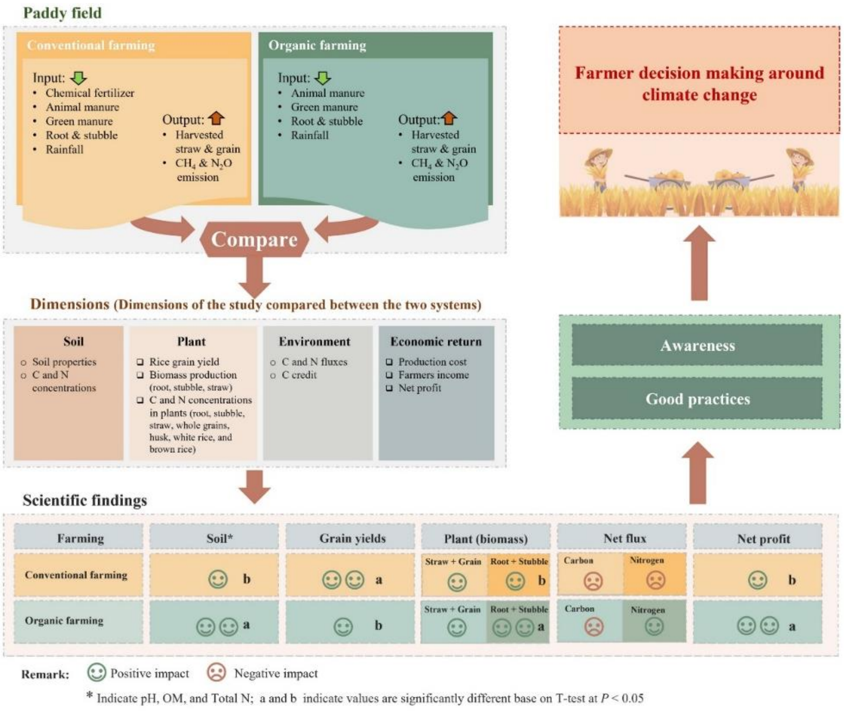
2021; Zhou et al., 2020). Mineral and organic fertilizer utilization are the major soil N influxes (Cui et al., 2020). Both C and N effluxes from rice paddies could be related to harvested crop removal and atmospheric greenhouse gas emission (Witt et al., 2000).

A recent study in the Japanese soil-rice system revealed a net N accumulation accomplished by combined chemical and organic fertilizers as the main N influxes, with straw removal as the primary N efflux (Nguyen et al., 2020a). Conversely, the N depletion associated with the harvested rice contributed 61-68% of the total N loss, with chemical fertilization, crop residue, and animal manure incorporation causing a net N depletion (Sridevi and Venkata Ramana, 2016). Paddy rice production under anaerobic conditions could promote soil C sequestration by decreasing the SOM decomposition rate (Qiu et al., 2018) and enhancing net C and N accumulations (Liu et al., 2018).

Agricultural practices are critical factors for C and N cycling in soil-plant systems (Yadav et al., 2019). Two typical farming systems are conventional farming (CF) and organic farming (OF). Regardless of agrochemical utilization, the CF system can apply chemical and organic fertilizers, ensuring high yields from large-scale production (Arunrat et al., 2017). Much research has reported that the CF systems with high chemical-N fertilization have exacerbated nitrous oxide emissions (Rahmawati et al., 2015; Robertson et al., 2000). Conversely, OF systems supplying plant nutrients solely from organic materials may result in low crop yields (Seufert et al., 2012; Timsina, 2018). Much studies have demonstrated that organic amendment additions in the OF system could profoundly mitigate greenhouse gas emissions and promote net N accumulation in soil-rice systems (Qin et al., 2010; Rahmawati et al., 2015; Setyorini and Hartatik, 2021). The types and extents of C and N influxes are derived from the diverse agricultural practices affecting the yield, biomass, and net C and N fluxes of the soil-rice systems.

We hypothesized that CF and OF systems could have pronounced impacts on C and N cycling and their stock in soils and could cause long-term insecurity for sustainable rice production. Obtaining practical and effective rice paddy management measures that achieve C and N accumulations in soil-rice systems through proper management is an essential prerequisite to agricultural and environmental sustainability. Therefore, the objective of this study was to examine detailed measurements of the C and N fluxes in rice paddies in Thailand under CF and OF systems. The conceptual framework for this research is given Figure 1. This study should enhance understanding of how agricultural practices affect C and N fluxes, which can assist in the design of a strategy and policy to implement adaptive management for sustainable agriculture and the environment.



Farming	Soil*	Grain yields	Plant (biomass)		Net flux		Net profit
			Straw + Grain	Root + Stubble	Carbon	Nitrogen	
Conventional farming	☺ b	☺☺ a	☺	☺ b	☹	☹	☺ b
Organic farming	☺☺ a	☺ b	☺	☺☺ a	☹	☺	☺☺ a

* Indicate pH, OM, and Total N; a and b indicate values are significantly different base on T-test at $P < 0.05$

Figure 1. The conceptual framework for investigating biogeochemical cycling of carbon and nitrogen in rice production under conventional and organic farming

2. METHODOLOGY

2.1 Soil and rice sampling

This study investigated 63 pairs of soil and rice samples from Amnat Charoen Province, Thailand, where rice (*Oryza sativa*) is a major product (Figure 2). Jasmine rice, Khao Dawk Mali 105 (KDML105) variety is the most common rice variety in the studied area. This is a photosensitive rice with a typical cultivation period from mid-July to mid-December. One rice crop is grown annually. The studied area was in the rainfed zone with average annual temperature and rainfall of 27.6ºC and 1,349 mm/year, respectively (Figure 3). The limited irrigation areas allow for the cultivation of some other crops. The soil and rice samples were collected on a grid (6 km × 6 km) that covered major representative soil series (Re, Kt, Ub, and Ng) in the studied area. Detailed sample coordinates are given in Table S1. The soils in this area have been mainly associated with sandstone.

At harvest in late November to early December 2019, composite and undisturbed soil samples from each defined location were taken from the topsoil layer at 0-20 cm depth. The soil samples (n=63) were air-dried, ground, and passed through a 2 mm sieve for further physiochemical analysis. The finely ground soil materials (<0.5 mm) were prepared for analyses of organic carbon (OC), total carbon (TC), and total nitrogen (TN). The samples were preserved in plastic containers at room temperature before the chemical analyses. The undisturbed samples of soil cores were determined for bulk density.

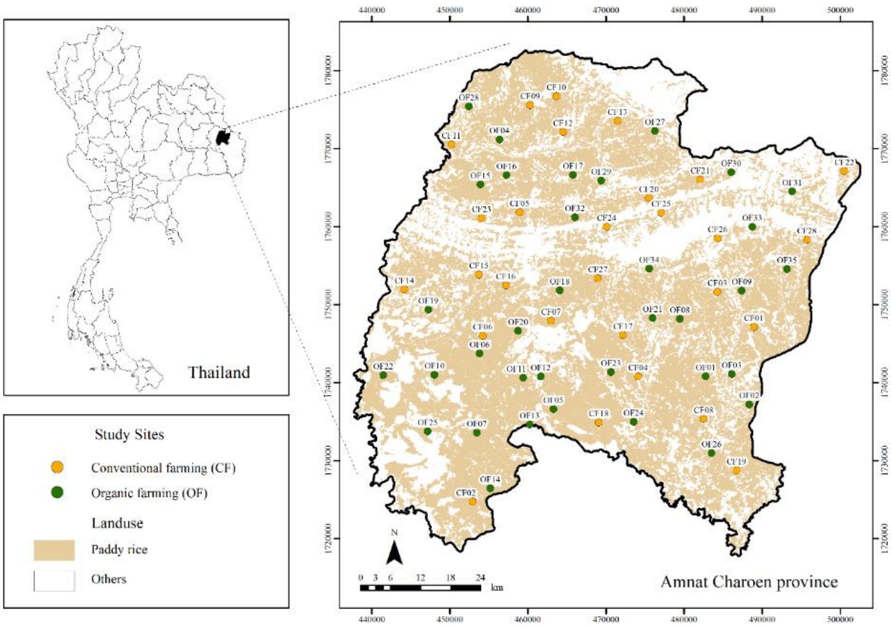


Figure 2. Sampling locations of soil and rice pairs (n=63) in Amnat Charoen Province, Thailand. Orange and green symbols indicate conventional farming (CF, n=28) and organic farming (OF, n=35), respectively.

For rice sampling and data collection, rice straw was manually cut at about 60 cm above the soil surface in the same paddy field where the soil samples were collected. This cutting height reflected the common practice of hand-harvesting by farmers. Such a height allows more stubble to remain in the field relative to machine harvesting (average cut height is 30 cm above the soil surface). Biomass samples of roots, stubble, and straw (combined panicles, leaf, and stem) were collected from a 1 m × 1 m area. The roots and stubble were carefully removed from each soil sample and thoroughly washed with surface water. The samples were rinsed with tap water on arrival at the laboratory, and deionized (DI) water was used for the last washing step. The rice grain yield was taken from an area of 2 m × 2 m and reported at 14% (w/w) moisture content. Whole grains were dehusked and polished using a small milling machine; the corresponding yields of brown and white rice grains were recorded. All biomass weights were recorded after oven-drying at 65°C until constant weight. The plant samples were ground and preserved in plastic containers before analyses. The resultant seven rice parts (roots, stubble, straw, whole grains, husk, white rice, and brown rice) were used for the subsequent C and N measurements.

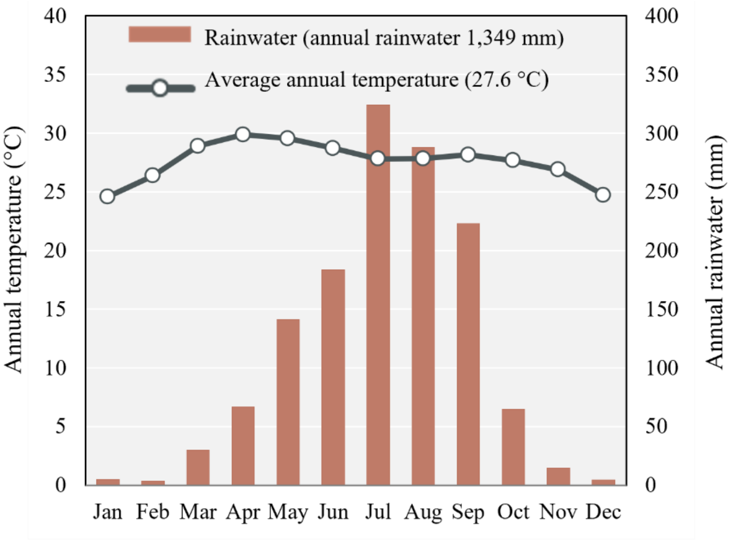


Figure 3. Average values of annual temperature and annual rainwater in Amnat Charoen Province, Thailand 2010-2019

2.2 Soil management data

The soil and fertilizer management regime for each location was obtained based on rice farmer interviews (n=63). The soil-rice management data, including the rates and types of chemical and organic fertilizers and green manure utilization applied in each area, were also collected during the interview; together these were used to calculate the C and N fluxes in the soil-rice systems. The C and N effluxes from harvested crops were calculated from the rice biomass and the C and N contents in all plant parts. Conventional farming (CF, n=28) and organic rice farming (OF, n=35) systems were observed in the studied area. The OF system was certified according to European or Thai organic standards (Organic Agriculture Certification Thailand, 2019).

Economic returns, including the production cost, the farmers income, and net profit, were also estimated for each location. The production costs in our study were calculated based on information provided by the respondents to the questionnaire on the inputs of rice cultivation, including chemical fertilizer, animal manure, and green manure utilization. Farmer income was solely from rice sales, calculated from the rice yield and price. The yield was measured at each location. The price was derived from Office of Agricultural Economics (2021). Net profit was the difference between the production cost and the rice sale income. Carbon credits were determined based on the tonnes of carbon dioxide equivalent (t CO_2e) of soil C stock and rice biomass (root and stubble incorporation) using an average price of 0.80 USD/t CO_2e (USD 1=THB 31.5) for biomass trading volume (Thailand Greenhouse Gas Management Organization, 2021).

2.3 Soil analysis

The physicochemical analyses were carried out using standard procedures, with details of the analysis described by Sparks et al. (1996). The soil texture and bulk density were determined using a hydrometer and soil core methods, respectively. The soil pH was measured using a soil-to-water ratio of 1:1. Organic matter (OM) was measured using the Walkley-Black wet oxidation method (Walkley and Black, 1934). Available phosphorus (P) was extracted using Bray-II extracting solution. The cation exchange capacity (CEC) and exchangeable bases (Ca, Mg, Na, and K) were obtained using the 1 M NH_4OAc (pH 7.0) method. The concentrations of Ca, Mg, Na, and K in the NH_4OAc extract were determined using atomic absorption spectroscopy.

2.4 Carbon and nitrogen analyses in soils and rice plants

For C and N determination in the soil and rice samples, total carbon (TC) and total nitrogen (TN) in the soil samples were measured using a dry combustion method (ISO, 1995). Approximately 10-20 mg of finely ground soil samples were weighed in tin capsules and measured using an NCS analyzer (Elementar, Flash 2000 Series, Thermo Scientific) combusted at 900°C. All seven plant parts (roots, stubble, straw, whole grains, husk, white rice, and brown rice) were measured for their TC and TN concentrations using the same procedure. Duplicates of an organic analytical standard (acetanilide OAS) were conducted to check the result accuracy of each batch (n=63). The accuracy levels for C and N in the samples was excellent at 100.15±0.25 and 100.60±0.44%, respectively.

2.5 Carbon and nitrogen stocks and fluxes in soil-rice systems

The total C and N stocks in the topsoil layer for each location were calculated by multiplying the C and N concentrations in the soil samples with their respective bulk densities and a soil depth of 20 cm (the common depth of paddy surface soils). The C stock and N stocks were reported as the total mass of the respective total C (Mg C/ha) and N (kg N/ha) in soils.

Net C flux was calculated from the difference between C influxes and effluxes. The C influxes consisted of the C concentrations from the roots and stubble and the animal and green manure applied to the soils. The C effluxes were the C concentrations from the harvested straw and grain and the CH_4 emission. Typically, the straw is completely removed from the field for sale or as cow fodder, some of which is later recycled in the form of cow manure. Rice stubble burning is rare in the studied area because farmers can only grow one rice crop annually and so there is no haste regarding land preparation for a second rice crop. The CH_4 emission was based on the IPCC Guidelines (IPCC, 2006), as shown in the equation:

$$\mathrm{CH_4} = \mathrm{t} \times \left(\mathrm{SF_w} \times \mathrm{SF_p} \times \mathrm{SF_0}\right) \times \frac{12}{16} \times \frac{1}{1000}$$

Where; CH_4 is the C released from methane emission for each area (mg C/ha), t is the rice cultivation period (115 days in this study), SF_w is the scaling factor to account for the differences in water regimes during the cultivation period, SF_p is the scaling factor to account for the differences in water regimes in the season before the cultivation period, and SF_0 is the scaling factor to account for differences in the types and amounts of applied organic amendments calculated as:

$$\mathrm{SF_0} = \left(1 + \sum \mathrm{ROA_i} \times \mathrm{CFOA_i}\right)^{0.59}$$

Where; ROA_i is the application rate of organic amendment i in dry weight for straw and fresh weight for other amendments (ton/ha), and $CFOA_i$ is the conversion factor for organic amendment i in terms of its relative effect relative to straw applied shortly before cultivation.

The N fluxes were calculated from the N influx and efflux differences. The N influxes consisted of the N contents from incorporating roots and stubble, fertilizer, animal, and green manure additions, and rainfall. The influxes from fertilizers, manure, and green manure were calculated using their respective application rates and N concentrations. The rainfall N was estimated from rainfall records in the studied area with the NO_3^- and NH_4^+ concentrations based on those reported by Panyakapo and Onchang (2008). The N effluxes were calculated from the N concentrations from harvested straw and grain as well as from N_2O emissions.

The direct and indirect N_2O emissions (reported as kg N/ha/year) were based on the Tier 1 IPCC Guidelines (IPCC, 2006), as shown in the equations:

$$\text{Direct } \mathrm{N_2O} \text{ emission} = \left[\left(\mathrm{F_{SN}} + \mathrm{F_{ON}} + \mathrm{F_{CR}} + \mathrm{F_{SOM}}\right) \times \mathrm{EF_{1FR}}\right]$$

Where; F_{SN}, F_{ON}, and F_{CR} are the annual amounts of chemical-N fertilizer, organic manure, and crop residues applied to soils, respectively (kg N/year), F_{SOM} is the annual amount of mineralized N related to C loss from soils (kg N/year), and EF_{1FR} is the emission factor for N_2O emission from N inputs to flooded rice.

The F_{SOM} value was computed as:

$$\mathrm{F_{SOM}} = \sum \left[\Delta \mathrm{C_{Mineral}} \times \frac{1}{\mathrm{R}}\right] \times 1000$$

Where; $\Delta C_{Mineral}$ is the average annual loss of soil carbon for paddy rice (t C/ha/year) and R is the C-to-N ratio of the soil organic matter at each location. The calculated carbon mineralization data were derived from Arunrat et al. (2018), whose study was conducted on the same type of coarse soil texture in the same region as in the current study area.

$$\text{Inirect } \mathrm{N_2O} \text{ emission} = \left[\mathrm{F_{SN}} \times \mathrm{Frac_{GASF}} + \mathrm{F_{ON}} \times \mathrm{Frac_{GASM}}\right] \times \mathrm{EF_4} + \left[\left(\mathrm{F_{SN}} + \mathrm{F_{ON}} + \mathrm{F_{CR}} + \mathrm{F_{SOM}}\right) \times \mathrm{Frac_{Leach}} \times \mathrm{EF_5}\right]$$

Where; $Frac_{GASF}$ and $Frac_{GASM}$ are the N fractions of the respective synthetic and applied organic N fertilizer that volatilizes as NH_3 and NO_x, whereas the EF_4 is the emission factor for N_2O emissions from atmospheric deposition of N in soils and water, $Frac_{Leach}$ is the fraction of all added N that is mineralized in managed soils in regions where leaching/runoff occurs, and EF_5 is the emission factor for N_2O emissions from N leaching and runoff. All emission factors relevant to the CH_4 and N_2O emissions applied in this study are provided in Table 1. Details of the C and N influxes from chemical fertilizers, animal, and green manures are given in Table S2.

The changes in total C and N stocks in soils were estimated under two schemes: 1) removal and incorporation of straw as:

Soil C stock change=Total C stock+n C fluxes (with and without straw incorporation)

Soil N stock change=Total N stock+n N fluxes (with and without straw incorporation),

Where; total C and N stocks are the total C and N stocks of the year i at each location and i indicates the year of projection (n=1-10).

2.6 Statistical analysis

Normality of the data was checked using the Shapiro-Wilk test. The mean differences in soil properties, the C and N contents in each rice part, soil stock and fluxes of C and N, the economic return (production cost, farmers income, net profit, and carbon credit from soil C stock and rice biomass) between the two farming systems were analyzed using a t-test. Mean differences of the C and N contents in the different rice parts were tested using an F-test and ANOVA. All statistical analyses were tested at a significance level of 0.05.

Table 1. Relevant emission factors based on IPCC Guideline (IPCC, 2006) used for calculating CH_4 and N_2O emissions in this study

Abbreviation	Description	Values and specific notes
CH_4 emission		
SF_w	Scaling factor to account for the differences in water regime during the cultivation period	0.27 for regular rainfed
SF_p	Scaling factor to account for the differences in water regime in the season before the cultivation period	0.68 for non-flooded pre-season >180 days
$CFOA_i$	Conversion factor for organic amendment i in terms of its relative effect with respect to straw applied shortly before cultivation	0.29 for straw incorporation >30days before cultivation, 0.14 for animal manure, and 0.50 for green manure
N_2O emission		
EF_{1FR}	Emission factor for N_2O emissions from N inputs to flooded rice	0.003
$\Delta C_{Mineral}{}^1$	Average annual loss of soil carbon for paddy rice (t C/ha)	1.173
$Frac_{GASF}$	Fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x	0.1
$Frac_{GASM}$	Fraction of applied organic N fertilizer materials that volatilizes as NH_3 and NO_x	0.2
$Frac_{Leach}$	Fraction of all N added mineralized in managed soils in regions where leaching/runoff occurs	0.3
EF_4	Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces	0.01
EF_5	Emission factor for N_2O emissions from N leaching and runoff	0.0075

[1] $\Delta C_{Mineral}$ is obtained from Arunrat et al. (2018)

3. RESULTS

3.1 Soil characteristics

The physicochemical properties of the studied paddy soils (n=63) under conventional farming (CF, n=28), and organic farming (OF, n=35) systems varied substantially among the locations tested within each rice farming system (Table 2). Sandy loam was the most common soil texture in the studied area on 37 sites. The soil pH varied greatly from extremely acidic to moderately alkaline. The OM and TC contents varied from very low to slightly high, while the TN content ranged from low to high. The available P varied from very low to very high. The CEC ranged from very low to low, whereas the exchangeable Ca, exchangeable Mg, and exchangeable Na varied between very low and moderate, and exchangeable K varied between very low to very high.

Based on average data, the studied soils were sandy loam with the bulk density not affecting the penetration of plant roots (BD=1.47 g/cm). The soils were acidic (pH=5.14) with very low contents of TC (4.65 g/kg), TN (0.82 g/kg), and exchangeable Ca (1.22 cmol$_c$/kg), low contents of exchangeable Mg (0.31 cmol$_c$/kg), exchangeable Na (0.19 cmol$_c$/kg), and exchangeable K (0.07 cmol$_c$/kg), and a moderately low level of available P (9.35 mg/kg). Comparing both farming systems, the OF system soils had significantly higher pH, OM, and TN values than those in the CF system. The available P and total C contents in the soils of the OF system had higher average values than for the CF system but none were at a significant level.

Table 2. Range (minimum-maximum) and average (mean±SD) of soil properties in topsoil (0-20 cm depth) for paddy rice production from conventional farming (CF, n=28) and organic farming (OF, n=35)

Practice		pH[1] (H$_2$O)	OM (g/kg)	Total C (g/kg)	Total N (g/kg)	Avail.P (mg/kg)	CEC (cmol$_c$/kg)	Exch.Ca (cmol$_c$/kg)	Exch.Mg (cmol$_c$/kg)	Exch.Na (cmol$_c$/kg)	Exch.K (cmol$_c$/kg)	BD (g/cm)	Sand (%)	Silt (%)	Clay (%)
All	Min-Max	4.30-7.95	2.90-29.0	1.81-18.55	0.36-1.94	1.00-65.50	0.72-12.07	0.16-9.18	0.03-2.97	0.05-0.66	0.02-0.40	1.25-1.69	40-88	6-45	2-30
Location	Mean±SD	5.14±0.66	8.50±3.70	4.65±2.17	0.82±0.28	9.35±9.35	3.10±2.20	1.22±1.64	0.31±0.50	0.19±0.12	0.07±0.07	1.47±0.09	72±11	19±8	10±6
CF	Min-Max	4.30-6.05	2.90-12.0	1.81-7.02	0.36-0.84	1.00-24.00	0.72-12.07	0.16-7.50	0.04-2.97	0.05-0.52	0.02-0.24	1.32-1.62	40-88	6-45	5-27
	Mean±SD	4.95±0.48^b	7.34±2.13^b	4.43±1.24	0.64±0.13^b	7.16±5.16	3.43±2.58	1.37±1.70	0.31±0.55	0.19±0.12	0.06±0.06	1.49±0.08	71±12	19±10	10±5
OF	Min-Max	4.45-7.95	4.07-28.9	2.32-18.55	0.51-1.94	2.00-65.50	0.75-9.90	0.24-9.18	0.03-2.22	0.05-0.66	0.02-0.40	1.25-1.69	49-87	8-36	2-30
	Mean±SD	5.29±0.74^a	9.41±4.41^a	4.82±2.70	0.97±0.29^a	11.1±13.26	2.84±1.84	1.11±1.60	0.32±0.46	0.19±0.12	0.07±0.08	1.47±0.09	72±10	19±7	9±6
T-test		*	*	ns	*	ns	ns	ns	ns	ns	ns	-	-	-	-
CV (%)		12.76	43.63	46.69	34.23	113.13	67.54	133.68	158.40	63.38	97.59	-	-	-	-

[1] OM: Organic matter; Total C: Total Carbon; Total N: Total Nitrogen; Avail. P: Bray-II extractable P; CEC: Cation exchange capacity; Exch. Ca, Mg, Na, and K: NH$_4$OAc exchangeable Ca, Mg, Na, and K respectively; BD: Bulk density; CV: Coefficient of variation. Mean values with different lowercase superscripts are significantly different based on t-test at $p<0.05$.

3.2 Rice grain yield and biomass production

The rice grain yield and biomass production in different rice parts differed among the locations and farming systems (Figure 4). The rice grain yield in the CF system (3.53 ton/ha) produced a significantly higher grain yield than the OF system (3.03 ton/ha). The combined straw and grain biomass on a dry matter basis in the CF system (7.04 ton/ha) was also higher than for the OF system (6.32 ton/ha) but none of these components were significantly different from each other. Conversely, the combined root and stubble biomass in the OF system (3.26 ton/ha) was significantly more abundant than in the CF system (2.35 ton/ha). The low rice yield observed in this study was typical for this Thai fragrant rice compared to other varieties (Suwanmontri et al., 2021).

3.3 Carbon and nitrogen concentrations in rice parts

The concentrations of C and N in the different rice parts (root, stubble, straw, whole grain, husk, brown rice, and white rice) under both the CF and OF systems are presented in Figure 5. The average C concentrations in the different plant parts for each farming system were significantly different (Table S3). The average C concentrations in the whole grain (CF=404 and OF=409 g C/kg) and straw (CF=402 and OF=406 g C/kg) were significantly higher than in the stubble (CF=395 and OF=398 g C/kg) and roots (CF=334 and OF=339 g C/kg).

The average N concentrations were significantly different among the rice parts. There was more N in the whole grain (CF=10.06 and OF=10.48 g N/kg), but accumulated less in the roots (CF=6.77 and OF=7.51 g N/kg), straw (CF=5.96 and OF=6.12 g N/kg), and stubble (CF=3.98 and OF=4.26 g N/kg), respectively. The brown grain had the highest N concentration (CF=12.82 and OF=12.64 g N/kg) in the whole grain but was lowest in the husk (CF=3.56 and OF=3.70 g N/kg), indicating that rice bran contained the greatest accumulation of the N fraction in the rice plants.

3.4 Carbon and nitrogen fluxes in paddy rice systems

Since C and N are the primary plant nutrient elements for sustainable paddy rice production, the C and N flux differences (influxes and effluxes) for the CF and OF systems were measured (Table 3). Our C mass fluxes demonstrated that the current C influxes varied greatly from 0.97 to 1.63 mg C/ha/year

($\bar{x}$=2.64 mg C/ha/year), depending on the location and farming system (Table S4).

In 62 of the 63 sites (98%), the C mass fluxes showed net depletion, indicating a severe decline in soil C in these rice production systems. The C mass in the OF system (-3.05 to +0.12 mg C/ha/year, $\bar{x}$=-1.50 mg C/ha/year) was less depleted than in the CF system (-4.78 to -0.95 mg C/ha/year, $\bar{x}$=-2.37 mg C/ha/year) (Table 3). This could be primarily attributed to the considerable influxes of biomass (roots and stubble) and animal manure added to the soils in the OF systems. The rice roots and stubble incorporated into the soils contributed the most significant C influxes to paddy rice production, corresponding to 58-67% of the total C influxes. The C influxes from the roots and stubble in the OF system (0.46-2.02 mg C/ha/year, $\bar{x}$=1.21 mg C/ha/year) were significantly higher than in the CF system (0.19-1.71 mg C/ha/year, $\bar{x}$=0.84 mg C/ha/year). The C influx from animal manure in the OF system ($\bar{x}$=0.58 mg C/ha/year) was also more abundant than in the CF system ($\bar{x}$ = 0.29 mg C/ha/year), corresponding to 23-28% of the total C influxes (Table 3).

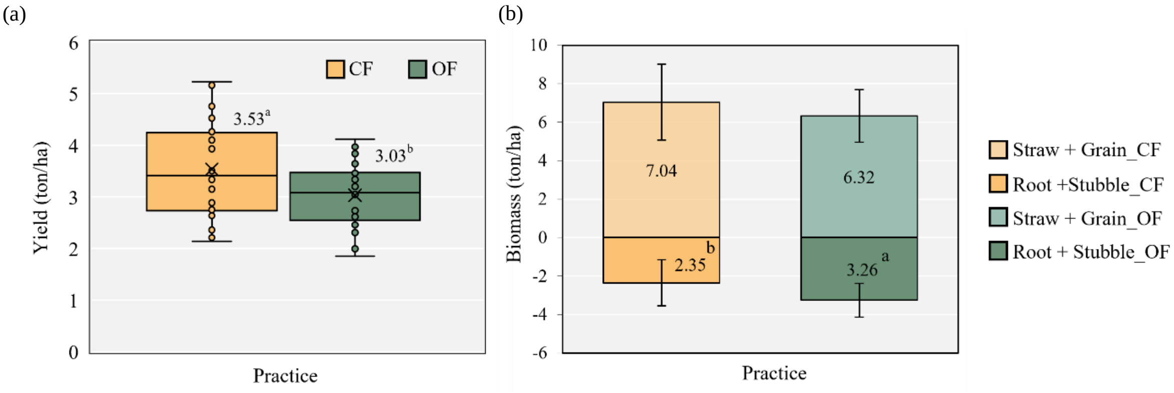


Figure 4. Rice grain yield box plot (a) and biomass production bar plot in different parts of rice plant parts (b) under conventional farming (CF, n=28) and organic farming (OF, n=35) systems. Error bars for (b) indicate standard variation of data in each system. Different lowercase superscripts indicate significant difference based on t-test at p<0.05.

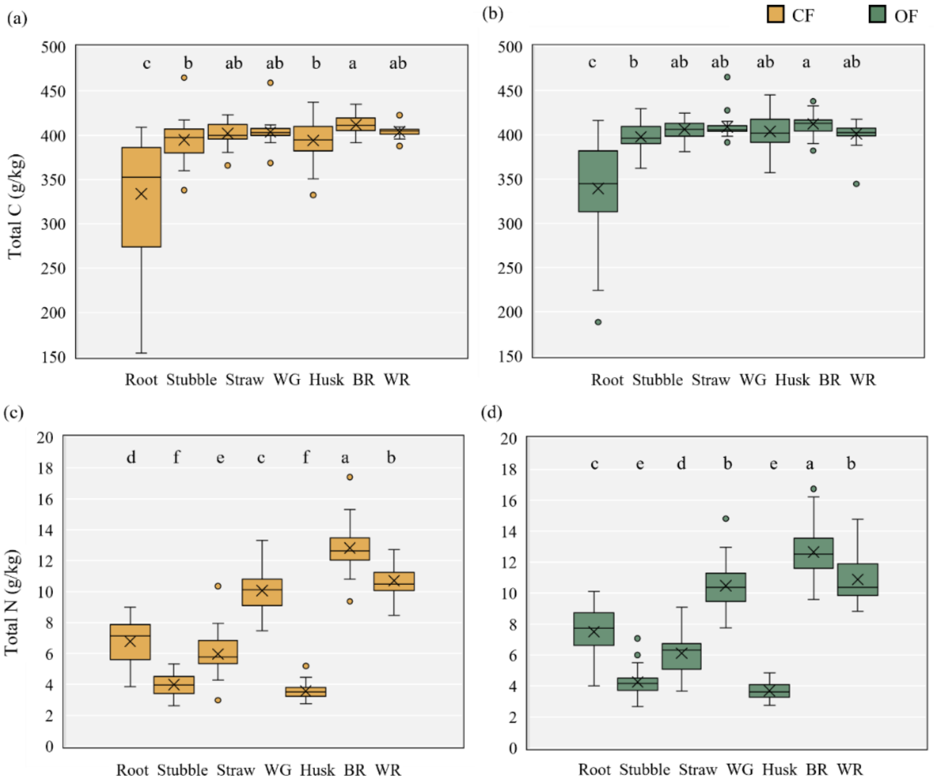


Figure 5. Concentrations of C (a, b) and N (c, d) in different rice parts under conventional farming (CF, n=28) and organic farming (OF, n=35) systems. Different lowercase letters above box plots indicate significant differences based on F-test at p<0.05. WG, BR, and WR denote whole grain, brown rice, and white rice, respectively.

Table 3. Range (minimum-maximum) and average (mean±SD) values of C and N stock in soils, and fluxes of C and N in paddy rice production under conventional farming (CF, n=28) and organic farming (OF, n=35)

Parameter	Carbon (mg C/ha/year)					Nitrogen (kg N/ha/year)				
	Conventional farming		Organic farming		T-test	Conventional farming		Organic farming		T-test
	Min-Max	Mean±SD	Min-Max	Mean±SD		Min-Max	Mean±SD	Min-Max	Mean±SD	
Soil C and N stock	5.87-22.2	13.17±3.83	6.65-54.5	14.12±7.99	ns	1,121-2,656	1,905±384^{b}	1,516-5,702	2,827±842	*
Influx										
Chemical fertilizer	-	-	-	-	-	9.38-57.2	22.25±14.91^{a}	0-0	0±0^{b}	*
Green manure	0-1.79	0.13±0.47	0-1.79	0.31±0.68	ns	0-85.0	6.07±22.29	0-85.0	14.6±32.5	ns
Manure	0-1.34	0.29±0.34^{b}	0-2.00	0.58±0.46^{a}	*	0-50.3	11.4±13.11^{b}	0-75.4	23.5±17.8^{a}	*
Rainfall	-	-	-	-	-	0.40-0.55	0.46±0.06	0.40-0.55	0.46±0.06	ns
Roots	0.05-0.63	0.27±0.17^{b}	0.16-0.79	0.45±0.15^{a}	*	0.81-15.36	5.75±3.93^{b}	4.52-21.3	10.2±4.27^{a}	*
Stubble	0.14-1.08	0.57±0.28^{b}	0.30-1.23	0.76±0.21^{a}	*	1.46-12.38	5.74±2.9^{b}	2.84-16.5	8.21±3.05^{a}	*
Total	0.21-3.03	1.25±0.58^{b}	0.83-4.04	2.10±0.84^{a}	*	13.04-118.0	51.7±25.0	13.0-142.9	57.0±33.6	ns
Efflux										
Straw	2.75-0.68	0.44±1.56	0.95-2.45	1.46±0.37	ns	8.23-51.2	23.4±9.07	11.3-43.0	21.8±6.37	ns
Grain	0.68-2.11	1.27±0.38	0.57-1.75	1.11±0.26	ns	15.0-58.2	31.6±10.2	14.3-47.9	28.5±7.42	ns
CH_4 emission	0.30-1.25	0.80±0.21^{b}	0.56-1.33	1.02±0.17	*	-	-	-	-	-
N_2O emission	-	-	-	-	-	0.68-2.02	1.27±0.32^{b}	0.79-3.66	1.80±0.71^{a}	*
Total	2.03-6.12	3.63±0.92	2.33-5.06	3.60±0.63	ns	24.3-110.5	56.3±17.45	29.2-86.1	52.1±12.0	ns
Flux difference	(-4.78)-(-0.95)	(-2.37)± 0.83^{b}	(-3.05)-(+0.12)	(-1.50)± 0.80^{a}	*	(-59.4)-(+56.9)	(-4.56)± 28.26	(-42.7)-(+70.8)	4.87±31.4	ns

(*) and ns in the t-test column indicate values are significantly different and not significantly different, respectively, at $p<0.05$. Mean values with different lowercase superscripts are significantly different based on t-test at $p<0.05$. The period of flux is one year.

The harvested straw and grain accounted for the most significant part of the total C effluxes (71-78%), for which the CF system (1.36-4.86 mg C/ha/year, $\bar{x}$=2.83 mg C/ha/year) was higher than for the OF system (1.52-4.20 mg C/ha/year, $\bar{x}$=2.57 mg C/ha/year). There were no significant differences in the C effluxes between the systems. The C efflux from straw in the CF and OF systems contributed 53-57% of the combined straw and grain C effluxes, indicating that considerable C from the rice straw was removed from the paddy fields and could be recycled into the soil-rice systems. The calculated CH_4 emission efflux ranged from 0.80 to 1.02 mg C/ha/year (Table S5), corresponding to 22-28% of the total C effluxes. The CH_4 efflux in the OF system ($\bar{x}$=1.02 mg C/ha/year) was significantly higher than that in the CF system ($\bar{x}$=0.80 mg C/ha/year).

The N mass fluxes revealed net accumulations in the OF system (-42.7 to +70.8 kg N/ha/year, $\bar{x}$=+4.87 kg N/ha/year) but showed net depletions in the CF system (-59.4 to +56.9 kg N/ha/year, $\bar{x}$=-4.56 kg N/ha/year), as shown in Table 3. The large variation in N mass fluxes occurred because of the large variations in the chemical and organic fertilizer inputs. There was no significant difference between the two systems. N fertilization was the most critical N influx in the CF system (9.38-57.2 kg N/ha/year, $\bar{x}$=22.25 kg N/ha/year), corresponding to 42% of the total N influxes. Conversely, the animal manures (0-75.4 kg N/ha/year, $\bar{x}$=23.5 kg N/ha/year) and root and stubble incorporation (7.36-37.8 kg N/ha/year, $\bar{x}$=18.41 kg N/ha/year) were the two main N influxes for the OF system, corresponding to 41% and 32%, respectively. The N influx from precipitation was meager, accounting for only 0.8-0.9% of the total N influxes ($\bar{x}$=0.46 kg N/ha/year, Table S6).

Straw and grain harvests were the primary N effluxes for the CF ($\bar{x}$=55.0 kg N/ha/year) and the OF ($\bar{x}$=50.3 kg N/ha/year) systems. The N efflux from grains in both systems accounted for 57-58% of the combined straw and grain N effluxes. The N efflux from N_2O emission (1.27-1.80 kg N/ha/year) was very low (2-4%) compared to the total N effluxes (Table S5). The OF system ($\bar{x}$= 1.80 kg N/ha/year) had a significantly higher N_2O emission than the CF system ($\bar{x}$=1.27 kg N/ha/year).

3.5 Estimation of changes in carbon and nitrogen stocks and fluxes

Based on the mass fluxes of the C and N influxes and effluxes for our studied locations, we estimated the changes in the C and N stocks in the next 10 years under two scenarios: (1) current practice of straw removal (Figure 6) and (2) proposed measure of straw incorporation (Figure 7). The existing soil C stock in the CF system (5.87-22.18 mg C/ha, $\bar{x}$ =13.17 mg C/ha) was not significantly different from the OF system (6.65-54.5 mg C/ha, $\bar{x}$ =14.12 mg C/ha). Conversely, the current soil N stock in the OF system (1,516-5,702 kg N/ha, $\bar{x}$ = 2,827 kg N/ha) was significantly higher than in the CF system (1,121-2,656 kg N/ha, $\bar{x}$ =1,905 kg N/ha).

In the first scenario (straw removal practice), by the year 2030, the C soil stock declined critically from 13.17 mg C/ha to -10.58 mg C/ha for the CF system and from 14.12 mg C/ha to -0.83 mg C/ha for the OF system. Most importantly, the estimated soil C stock in the CF and OF systems severely declined and was exhausted by 2026 and 2029, respectively (Figures 6 (a) and (b)).

The second scenario (entire straw incorporation; Figures 7 (a) and (b) could turn the current net C depletion into a net accumulation of +0.19 mg C/ha for the CF system and of +0.96 mg C/ha for the OF system. Therefore, the estimations of the soil C stock in the next 10 years (up to 2030) considerably increased to 15.05 mg C/ha for the CF system and to 23.73 mg C/ha for the OF system. This C stock in the straw incorporation scenario was far greater than the unchanged practice scenario without the straw incorporation (-10.58 and -0.83 mg C/ha for the CF and OF systems, respectively). The soil C concentration increased to 5.08 g C/kg for the CF system and to 8.10 g C/kg for the OF system in the next 10 years, whereas those in the current measure were exhausted.

The soil N stock in the CF system slightly decreased from 1,905 kg N/ha to 1,860 kg N/ha in the next 10 years (Figure 6 (c)). Conversely, the N stock in the OF system slightly increased from 2,827 kg N/ha to 2,876 kg N/ha with stable soil N at a low level (Figure 6 (d)). With the straw incorporation over the next 10 years, the current net N depletion ($\bar{x}$=-4.56 kg N/ha) turned into a net N accumulation ($\bar{x}$=+42.15 kg N/ha) for the CF system and significantly enhanced the N accumulation from +4.87 kg N/ha to +48.39 kg N/ha for the OF system. By 2030, the N concentration for the CF and OF systems was expected to increase to 0.79 and 1.13 g N/kg, respectively.

Notably, the estimation was linearly based on the constant net C and N fluxes and thereby had some limitations as it did not consider the consequential effects of changes in C and N stocks to C and N effluxes. However, it was worth demonstrating that simple practices of straw incorporation (typically neglected by local farmers) could result in net C accumulation along with bolstering net N accumulation in both systems.

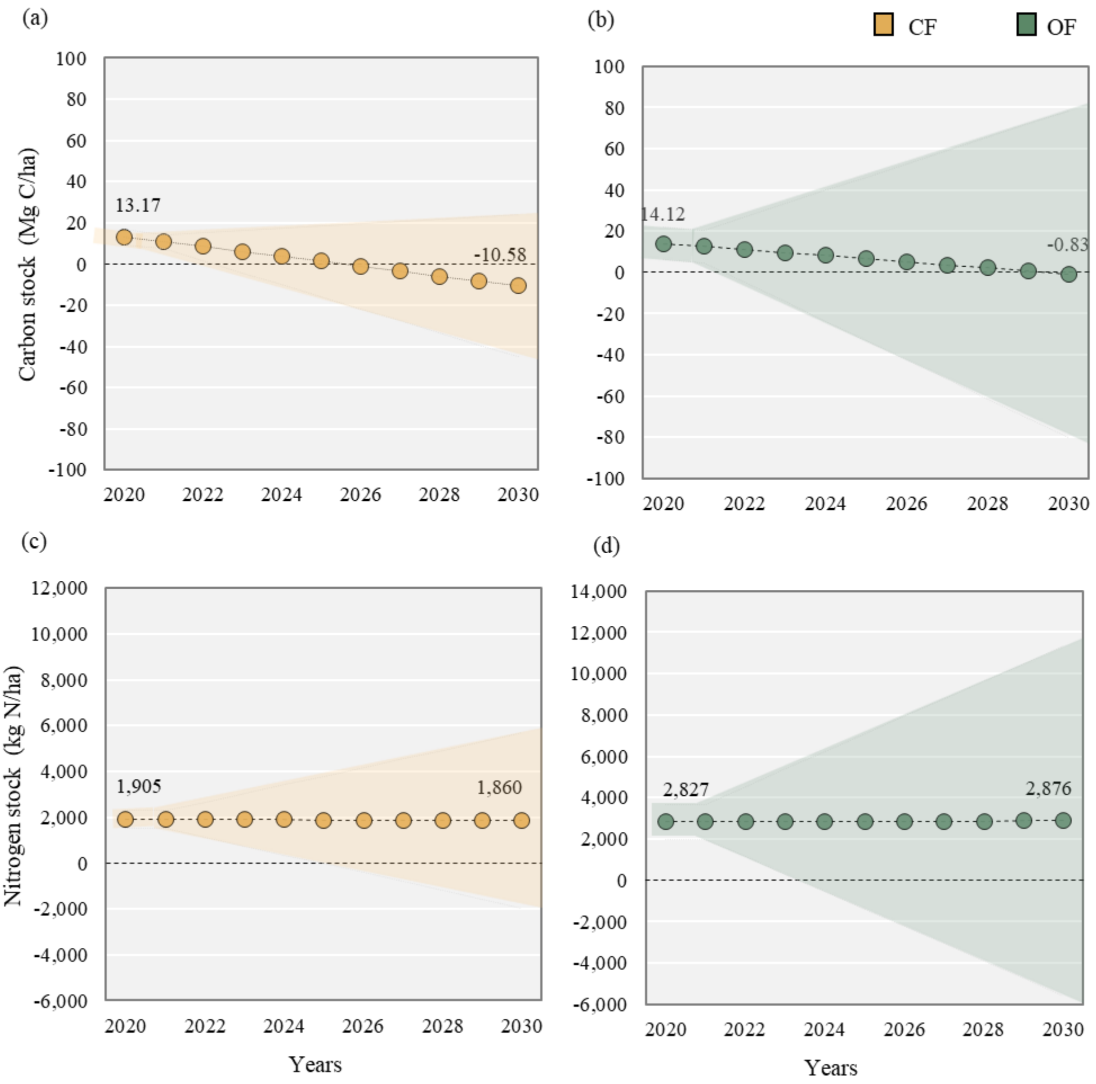


Figure 6. Estimation of changes in stocks of soil carbon (a, b) and nitrogen (c, d) under conventional farming (CF, n=28) and organic farming (OF, n=35) systems. Each data point indicates average values of soil C and N stocks with corresponding C and N fluxes. The orange and green shaded areas indicate standard deviation of entire dataset (n=63). The C fluxes were -2.37 mg C/ha for CF and -1.50 mg C/ha for OF. The N fluxes were -4.56 kg N/ha for CF and 4.87 kg N/ha for OF.

3.6 Estimation of values of rice production cost, farmers income, net profit, and carbon credits

For sustainability of rice production, the production cost, the farmers income, and net profit (Table 4) should be taken into consideration in addition to the rice grain yield. Although the CF system (3.53 ton/ha) had a significantly higher grain yield than the OF system (3.03 t/ha) (Table 3), the OF system (USD 1,729/ha) had significantly higher income from rice sales than the CF system (USD 1,458 /ha) due to the price of organic rice being higher than for regular rice of about USD 160/ton. Conversely, the CF system (USD 72/ha) had a significantly higher production cost (principally from chemical fertilizer input) than the OF system (USD 20/ha), which resulted in the net profit for the OF system (USD 1,710/ha) being significantly higher than for the CF system (USD 1,390/ha) by about USD 320/ha.

Based on the soil C stock and biomass production in our study (Table 3, Figure 4), we estimated the values of carbon credits in soil and biomass incorporation as an additional source of income. Considering the soil C stock from both systems (Table 4), the value of the carbon credits for soil C sequestration in the CF and the OF systems were USD 39/ha and USD 41/ha, respectively. The value of the carbon credits from the combined root and stubble in the CF system (USD 7/ha) was significantly lower than for the OF system (USD 10/ha). Conversely, considering straw incorporation to the soil, the carbon credit values from the straw in the CF system and OF system were respective USD 11.4/ha and USD 10.5/ha, respectively. The addition of the carbon credit for rice husk in the CF system (USD 1.8/ha) was slightly higher than for the OF system (USD 1.6/ha).

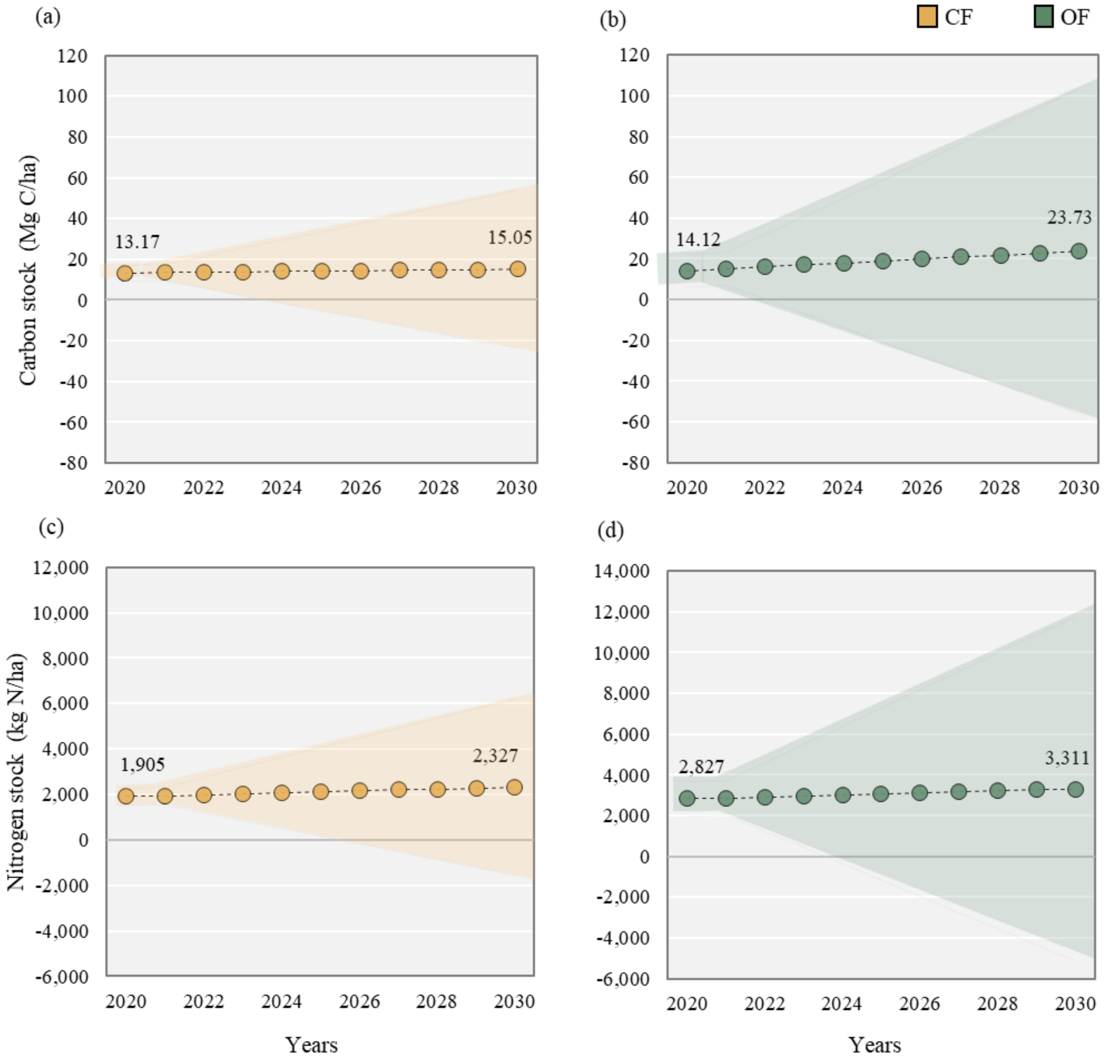


Figure 7. Estimated change in soil C (a, b) and N (c, d) stocks under both conventional (CF, n=28) and organic farming (OF, n=35) systems induced by straw incorporation. The orange and green shaded areas indicate standard deviation of data (n=63). The C fluxes were +0.19 mg C/ha for CF and +0.96 mg C/ha for OF, whereas the N fluxes were +42.15 kg N/ha for CF and +48.39 kg N/ha for OF.

Table 4. Range (minimum-maximum) and average (mean±SD) of production cost, income, net profit, and carbon credit from conventional farming (CF, n=28) and organic farming (OF, n=35), where the calculation is based on one crop season per year.

Practice		Production cost[1] (USD/ha)	Income[2] (USD/ha)	Net profit[3] (USD/ha)	Carbon credit[4] (USD/ha)			
					Soil	Root+stubble	Straw	Rice husk
CF	Min-Max	24-215	882-2,158	696-2,101	17-65	2-16	4.7-20.7	1-3
	Mean±SD	72±43^{a}	1,458±389^{b}	1,390±392^{b}	39±11	7±4^{b}	11.4±2.7	1.8±0.5^{a}
OF	Min-Max	3-57	1,056-2,351	1,040-2,342	19-160	4-14	6.9-18.1	1-2
	Mean±SD	20±14^{b}	1,729±345^{a}	1,710±346^{a}	41±23	10±3^{a}	10.5±2.7	1.6±0.3^{b}
T-test		*	*	*	ns	*	ns	*

[1] Production cost calculated from inputs for growing rice, including seed, chemical fertilizer, animal manure, and green manure utilization.

[2] Income is farmer income from rice sale calculated from yield and price of rice.

[3] Net profit is difference between production cost and rice sale income.

[4] Carbon credit estimated from tonnes of carbon dioxide equivalent (t CO_2e) of soil C stock and rice biomass with an average price of USD 0.80/t CO_2e.

(*) and ns in the t-test column indicate values are significantly different and not significantly different, respectively, at p<0.05. Mean values with different lowercase superscripts are significantly different based on t-test at p<0.05.

4. DISCUSSION

4.1 Effects of agricultural practices on carbon and nitrogen fluxes in paddy rice system

Agricultural practices exert a strong influence on yield as well as C and N fluxes in soil-rice systems. Several studies on farming practice impacts on the C and N fluxes and yield have reported there were variable effects on the C and N mass from a net accumulation to net depletion (Cheng et al., 2016; Cui et al., 2020; Mortensen et al., 2021; Nguyen et al., 2020a; Sridevi and Venkata Ramana, 2016; Witt et al., 2000; Yang et al., 2020). Many factors affect the influxes and effluxes of C and N, which vary among agricultural practices and sites. Manures, organic fertilizers, and harvested crop residues are documented to be the primary C influxes (Mortensen et al., 2021), but chemical and organic fertilizers and harvested crop residues are the major N influxes for arable soils (Cui et al., 2020). However, another study showed that the harvested crop removal and greenhouse gas emission could be key pools of C and N effluxes for rice paddies (Witt et al., 2000).

Nguyen et al. (2020a) revealed net N accumulation in a Japanese paddy rice system could be achieved by applying chemical N fertilizer, rice straw, and cow dung compost, with plant uptake being the primary N efflux. Nonetheless, Sridevi and Venkata Ramana (2016) showed that either chemical fertilizer and straw, or manure incorporation failed to meet the net N accumulation in Indian 25-year paddy rice cultivation. In addition to the influxes and effluxes of C and N, rice production under anaerobic conditions promoted SOM accumulation by lowering the SOM decomposition rate (Qiu et al., 2018), thereby leading to net C and N accumulations (Liu et al., 2018).

Our data demonstrated rainfed paddy rice cultivation in sandy soils under tropical environments resulted in net C depletions under both the CF and OF systems (Table 3). The CF system had a net N depletion, while the OF system had a net N accumulation. The distinct differences in the C and N fluxes were attributed to variations in the influxes and effluxes between the sites and farming systems. Collectively, harvested grain and straw biomass were the primary source of both C and N effluxes under field conditions in the current study. Conversely, the roots and stubble left in the fields and animal manure addition were the main C influxes to paddy soils. Such measures as entirely harvested straw and grains resulted in net C depletions in both farming systems. The animal and green manures dominated the N influxes for the OF system, resulting in net N accumulations. Conversely, chemical-N fertilizer and animal manure predominated the N influxes for the CF system and the net N depletions. The CH_4 emission contributed to a moderate proportion of the total C effluxes, while the N emission was paltry. The estimated CH_4 (0.80-1.02 Mg C/ha) and N_2O (1.27-1.80 kg N/ha) emission data, based on the IPCC Guideline (IPCC, 2006), were higher than the direct measurement values of CH_4 and N_2O emissions from coarse-textured paddy soils in a province nearby to the studied sites and ranged from 0.019 to 0.029 mg C/ha/season and from 0.075 to 0.088 kg N/ha/season (Malumpong et al., 2021). These variations could be attributed to the different types of soil and crop management at each location and inherent deviation reported by the IPCC Guideline (IPCC, 2006).

Paddy rice production under the OF system had significantly higher root and straw biomass than in the CF system (Figure 4) probably because the OF system supplied abundant organic materials compared to the CF system, contributing to a higher SOM concentration (Table 2). Organic materials, such as animal manure, have a circumneutral condition, which could elevate the soil pH value (Table 2). The organic amendments added to soils could compete with the reactive sites of clay minerals and Fe/Al oxyhydroxides in soils, thereby mitigating Al toxicity and promoting soil P availability (Haynes and Mokolobate, 2001). P is an essential plant nutrient that supports the increased density and length of small and lateral roots (Vejchasarn et al., 2016), resulting in more roots and stubble being left in the fields and building up soil C stocks. However, additions of organic matter to soils could promote CH_4 emission from paddy soils as observed in the current and other studies (Nguyen et al., 2020b; Zhang et al., 2018). Therefore, effective water management, such as an alternate wetting and drying cycle, should be implemented together with organic matter addition to concurrently promote C sequestration and demote CH_4 emission.

Based on the mass C flux calculation, straw recycling to soils could have the greatest potential to turn the net C depletion into net C accumulation under both farming systems. This procedure could enhance N accumulation in the soils and result in net N accumulation for the CF system. However, the critical challenge is that most rice farmers must adopt practical measures to incorporate such a large straw volume into their paddy fields. The high C-to-N ratio of the straw material (~70 in the current study), with a slow decomposition rate could induce N immobilization and hinder rice growth and yield. Rapid N immobilization occurred after straw addition to soils under both flooded and non-flooded conditions within 1-10 days. The fine soil particles served as the primary sink of the immobilized N, most of which (71-91% of the immobilized N) could be mineralized after 160 days (Said-Pullicino et al., 2014). Although it is only temporal immobilization, rice plants could experience an N deficit during the early rice-growing period. To resolve this concern, straw incorporation into the paddy rice system should be processed chemically (for example, using urea and molasses) and biologically (for example, using cellulolytic bacteria) and subsequently used as livestock fodder (Aquino et al., 2020), with any cow dung manure being returned to support paddy rice production. The combined incorporation of green manure and rice straw to soils could enhance both the soil chemical and microbiological properties and could be a promising measure for rice production, consistent with recent observations in Chinese paddy soils (Zhou et al., 2020)

Though the mass C flux calculation revealed that straw incorporation to sandy soils in the current study could cause net C accumulation and be expected to enhance the soil C concentration in the next 10 years, the estimated values in both farming systems would remain at a very low C level (5.08-7.98 g C/kg), likely due to the rapid decomposition rate of organic matter in sandy soils under tropical climates that could accelerate C loss from the soils (Puttaso et al., 2011). Recycling the straw and husk in the form of biochar with high stability (Manyà, 2012) could be another promising approach to gradually build up soil C sequestration for long-term rice production in addition to the above measure of fresh straw incorporation. Biochar addition could also decrease the leaching of several nutrients such as N, P, Ca, Mg, and Si from highly weathered soils (Aldana et al., 2021; Laird et al., 2010). Furthermore, the regular application of co-composting of animal manure with biochar and the use of biochar-based slow-release fertilizer (Hagemann et al., 2017) could be an effective strategy to resolve plant nutrient deficiency, C sequestration, and greenhouse gas emission in paddy rice production in sandy soils under tropical environments with a high organic matter decomposition rate and poor soil nutrient fertility.

4.2 Effects of rice residues on silicon addition into paddy system

Since rice is an Si-hyperaccumulator plant, its residues are Si-laden materials (Ma et al., 2006). Recycling of the Si-rich rice residues would also enhance the Si phytolith with a high available Si form compared to silicate minerals (Seyfferth and Fendorf, 2012). Si-rich agricultural residues have proved to be an effective material for mitigating As accumulation in rice grain (Leksungnoen et al., 2019; Limmer et al., 2018), which is a critical human health concern (Zhu et al., 2008). This measure is necessarily required for paddy soils to produce rice containing an As-safe level (Carey et al., 2020). Rice residues typically contain about 10% Si by weight. The incorporation of roots and stubble, straw, and husk could potentially supply Si equivalent to 0.05-0.54 ($\bar{x}$=0.29 ton Si/ha), 0.16-0.71 ($\bar{x}$=0.37 ton Si/ha), and 0.03-0.11 ton Si/ha ($\bar{x}$=0.06 ton Si/ha), respectively. Therefore, recycling all Si-rich residues (roots, stubble, straw, and husk) could enhance the Si contents by about 0.24-1.35 ton Si/ha ($\bar{x}$=0.72 ton Si/ha) for each crop cycle. The calculated Si contents from rice residues in the current study were lower than the values reported by Penido et al. (2016) for straw (0.5-1.5 ton Si/ha) and husk (0.07-0.20 ton Si/ha) from Bangladesh, Cambodia, China, and the USA. The lower calculated Si content in the straw and husk biomass in the current study may have been due to the nature of the rice cultivar growing in the study area with low yield and low biomass. The proposed measure of whole straw recycling for about 10 years with the potential to change the C and N accumulation levels could elevate the bioavailable Si level by 1.6-7.1 ton Si/ha (3.7 ton Si/ha).

4.3 Approach to sustainable rice farming practices

To make development more sustainable in the agricultural sector, the Thai government launched the first 20 year national strategy to lead the country toward security, prosperity, and sustainability. According to the current scientific findings, the OF system produced higher belowground rice residues (root and stubble) than the CF system, which enhanced soil organic carbon and increased soil health. Most importantly, increasing soil C sequestration is one of the emerging Sustainable Development Goals that have been proposed to provide urgent action to address climate change. Although the grain yield of the OF system was lower than for the CF system, the net profit of the OF system was greater than for CF system by approximately USD 320/ha. The carbon credits from the soil C stock and root and stubble incorporation for the OF system were also higher than for the CF system by about USD 5.5/ha. Clearly, organic rice farming was the more profitable and environmental friendly farming system. To build a better future, it should be highlighted as a lesson-learned and be advocated as good practice for rice farmers globally. All governments, not only in Thailand, should adopt this scientifically based, firm evidence to drive policy making, formulation, and implementation. Strategic plans, roadmaps, input subsidies, and an organic rice price guarantee that could motivate farmers to convert to or establish organic rice farms should be undertaken to put these activities into practical actions.

5. CONCLUSION

The investigation of C and N cycling in rainfed rice production under conventional and organic rice farming revealed that organic rice farming improved many soil properties, including pH, OM, total N, total C and available P compared to conventional rice farming. However, the conventional paddy rice farming provided higher rice yield than from organic rice farming by about 0.5 ton/ha. Organic farming enhanced root and stubble biomass, which promote soil carbon input. The most important C and N effluxes occurred through straw and grain harvesting. Therefore, the C mass fluxes revealed net C depletion for both the rice farming systems, whereas the N mass fluxes had a net N depletion for conventional farming and a net N accumulation for organic farming. The variation in the C and N influxes, including for the combined roots and stubble incorporation and chemical-N fertilizer and animal manure, caused differences in the net C and N fluxes for both systems. Straw incorporation to soils could potentially resolve the net C depletion and greatly elevate the net N accumulation in paddy sandy soils under a tropical environment. Recycling Si-rich residues could gradually build up plant-available Si that could benefit long-term paddy rice production with safe-As levels. Organic rice farming had higher net returns than the conventional rice farming by USD 320/ha. Overall, the scientific findings from the current study revealed that improving soil quality and achieving a higher net profit from rice production can encourage extrinsic motivated action to turn the interest into action to combat climate change and to develop sustainable soil quality.

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