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Changes in the soil C and N contents, C decomposition and N mineralization potentials in a rice paddy after long-term application of inorganic fertilizers and organic matter

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ABSTRACT

A long-term experiment on combined inorganic fertilizers and organic matter in paddy rice (*Oryza sativa* L.) cultivation began in May 1982 in Yamagata, northeastern Japan. In 2012, after the 31st harvest, soil samples were collected from five fertilizer treatments [(1) PK, (2) NPK, (3) NPK + 6 Mg ha^{-1} rice straw (RS), (4) NPK + 10 Mg ha^{-1} rice straw compost (CM1), and (5) NPK + 30 Mg ha^{-1} rice straw compost (CM3)], at five soil depths (0–5, 5–10, 10–15, 15–20 and 20–25 cm), to assess the changes in soil organic carbon (SOC) content and carbon (C) decomposition potential, total nitrogen (TN) content and nitrogen (N) mineralization potential resulting from long-term organic matter addition. The C decomposition potential was assessed based on the methane (CH_4) and carbon dioxide (CO_2) produced, while the N mineralization potential was determined from the potassium chloride (KCl)-extractable ammonium-nitrogen (NH_4^+-N), after 2, 4, 6 and 8 weeks of anaerobic incubation at 30°C in the laboratory. Compared to NPK treatment, SOC in the total 0–25 cm layer increased by 67.3, 21.0 and10.8%, and TN increased by 64.2, 19.7 and 10.6%, in CM3, RS and CM1, respectively, and SOC and TN showed a slight reduction in the PK treatment by 5.2 and 5.7%, respectively. Applying rice straw compost (10 Mg ha^{-1}) instead of rice straw (6 Mg ha^{-1}) to rice paddies reduced methane production by about 19% after the soils were measured under 8 weeks of anaerobic incubation at 30°C. Soil carbon decomposition potential (*Co*) and nitrogen mineralization potential (*No*) were highly correlated with the SOC and TN contents. The mean ratio of *Co*/*No* was 4.49, lower than the mean ratio of SOC/TN (13.49) for all treatments, which indicated that the easily decomposed organic matter was from soil microbial biomass and soil proteins.

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C and N contents; C decomposition potential; long-term experiment; N mineralization potential; rice paddy

1. Introduction

Rice (*Oryza sativa* L.) is one of the three main cereal crops, together with wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.), in the world. The world's rice production in 2014 amounted to 741 Mt, which was larger than that of wheat at 729 Mt (FAO 2015), while the rice harvest area amounted to163 Mha, which was less than that of wheat at 222 Mha in 2014 (FAO 2015). Rice paddies account for a large fraction of the wetland ecosystem and most of them are in Asian countries. The dynamics of carbon (C) and nitrogen (N) in submerged rice paddies are different from those of aerobic soil for wheat and maize, because submerged rice paddies are maintained at lower redox potentials (Takai 1970; Patrick and DeLaune 1972).

Long-term experiments (LTE) on continuous cropping systems using various agronomic and cultural management practices provide a direct method not only to determine their productivity and sustainability, but also to verify their environmental impact and effects on global climate change (Rasmussen *et al*. 1998; Körschens 2006). The LTE can provide observations of soil change and functioning across time scales of decades, data critical for biological, biogeochemical and environmental assessments of sustainability, predictions of soil productivity and soil–environment interactions (Richter *et al*. 2007; Hopkins *et al*. 2009). Changes in soil organic carbon (SOC) and total nitrogen (TN) contents and other chemical, microbiological and physical properties resulting from various long-term inorganic fertilizer and organic matter management practices have been investigated in many regions around the world, mostly in uplands (Smith *et al*. 1997; Grant *et al*. 2001; Blair *et al*. 2006; Peltre *et al*. 2012; Dimassi *et al*. 2013; Kätterer *et al*. 2014; Kumar *et al*. 2014). On the other hand, a few long-term studies on continuous lowland-rice cropping (2 or 3 times per year) have been reported from the Philippines (Pampolino *et al*. 2006), China (Yan *et al*. 2007; Tong *et al*. 2009; Dong *et al*. 2012) and India (Mandal *et al*. 2007; Nayak *et al*. 2009; Tripathi *et al*. 2014) in the humid-subtropical regions. Also, there are LTEs on rice and upland crops systems in the same regions but most of the data generated were limited to grain yield trends (Dawe *et al*. 2000; Yadav *et al*. 2000; Gami *et al*. 2001; Ladha *et al*. 2003; Padre *et al*. 2007). In

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the temperate regions, there are many single rice LTEs carried out in Japan. The oldest LTE was started in 1926 in Anjo, Aichi Prefecture (Kanamori 2000). In the early period, Japanese researchers mostly focused on the soil N fertility change and rice yields in rice LTEs (Koyama and App 1979; Gotoh *et al.* 1984; Inubushi *et al.* 1984). Recently, some researchers reported the simulated results of SOC changes in Japanese paddy soils using the RothC model with several rice LTEs carried out in Japan or with paddy-upland rotation (Shirato and Yokozawa 2005; Shirato *et al.* 2011).

Increasing soil organic matter has a significant impact on the mineralization and recycling of C and N (Romanya *et al.* 2011). However, in submerged rice paddies, organic C decomposition produces not only carbon dioxide (CO_2), but also methane (CH_4), which is the most important greenhouse gas after CO_2, responsible for approximately 20% of the anthropogenic global warming effect (IPCC 2007). Many researchers have also demonstrated that incorporation of rice straw and green manure into rice paddy soils dramatically increases CH_4 emissions (Yagi *et al.* 1997; Kimura *et al.* 2004), but application of rice straw compost only slightly increases CH_4 emissions (Yagi and Minami 1990; Watanabe *et al.* 1994). Therefore, a soil health assessment of long-term organic matter applications on rice paddy soils, based on the dynamics of C decomposition under anaerobic conditions, must include an accounting of CH_4 as well as CO_2 emission rates. This would have much relevance to the climate change mitigation efforts which are now focused on soil C. Many LTEs have reported the initial and final soil C and N contents from long-term organic matter additions in paddy rice systems, but changes in the amounts of C decomposition potential including CH_4 production, and N mineralization potential, which are essential in evaluating the performance and sustainability of an agroecosystem, are scarce.

The objective of this study was to determine the changes in SOC and TN contents, the C decomposition potential based on the CO_2 and CH_4 produced, and the N mineralization potential under anaerobic incubation, after long-term (31 years) additions of two types of organic matter – rice straw and rice straw compost, combined with NPK fertilizers. The C decomposition and N mineralization potentials were measured under anaerobic incubation to simulate the conditions in the rice paddy fields.

2. Materials and methods

2.1. Site description and treatments

The long-term experimental field is located at the Yamagata Integrated Agricultural Research Center, Yamagata, Japan (38° 15′N, 140°15′E), belonging to a typical humid temperate climate zone. The mean annual temperature at the site was 11.7°C and annual precipitation was 1163 mm in the past 30 years (1981–2010), according to data recorded at Yamagata Meteorological Station (JMA 2015). Rice is grown in the area from May to September, and the rice field is left fallow for the remaining 7 months per year. The long-term experiment began in May 1982 for the first rice growth season. The soil is classified as Inceptisol by US Soil Taxonomy (Cheng *et al.* 2007). The initial soil had a pH (H_2O) of 5.56, SOC of 8.9 g kg^{-1} and TN of 1.1 g kg^{-1} at a depth of 0–12 cm. The SOC and TN were measured by the Tyurin and Kjeldahl methods, respectively (Yamagata Agricultural Research Station 1983).

Soil samples were collected from the following treatment plots: (1) PK, (2) NPK, (3) NPK + 6 Mg ha^{-1} rice straw (RS), (4) NPK + 10 Mg ha^{-1} rice straw compost (CM1), and (5) NPK + 30 Mg ha^{-1} rice straw compost (CM3). There was no replication for each treatment. The area of each square plot was 100 m^2. NPK fertilizers were applied as ammonium sulfate, monocalcium phosphate and potassium chloride. Monocalcium phosphate was applied as basic fertilization, while ammonium sulfate and potassium chloride were applied twice as basic and additional fertilizations. The 6 Mg ha^{-1} rate of rice straw incorporation was estimated from the average straw yield that was returned to the soil in the rice straw treatment. The 10 Mg ha^{-1} rate of rice straw compost was the local convention recommended by the local government. The rice straw compost was produced outdoors without any material addition for about 2–3 years until the volume did not change. Normally, 6 Mg air-dried rice straw (10% water content) can produce about 8.6 Mg rice straw compost (75% water content) based on the 60% rice straw weight that was lost from the rice straw composting process in our experience. Descriptions of the treatments are given in Table 1. Rice straw was left on the soil surface after harvest and during the winter season. It was incorporated into the soil during the land preparation for the next rice cropping season. The rice straw was removed after harvest, leaving only the stubble in the PK, NPK, CM1 and CM3 treatments. The rice straw compost was incorporated during land preparation in the CM1 and CM3 treatments, while the NPK fertilizers were broadcasted before soil puddling and rice transplanting. Rice straw and rice straw compost were incorporated in the top 15 cm plow layer.

On 19 November 2012, after the 31st rice crop harvest, we collected the soil samples from the 0–5, 5–10, 10–15, 15–20 and 20–25 cm soil depths with a DIK-106B soil sampler (Daiki, Saitama, Japan). We collected soil samples down to 25 cm because the plow layer of rice paddy is from the surface to 15 cm, and rice roots mostly reached to 25 cm. Nine core soil samples were taken from each plot (treatment) equally, and three cores were mixed to make up one replicate sample for a total of three replicates (pseudo-

Table 1. Details of the amounts of inorganic fertilizer and organic matter applied in the five treatment plots for each year.

	Inorganic fertilizer ($kg\ ha^{-1}$)			Organic matter† ($Mg\ ha^{-1}$)	
Treatment	N	P_2O_5	K_2O	Rice straw	Rice straw compost
PK	0	68	83	0	0
NPK	80	68	83	0	0
RS	80	68	83	6	0
CM1	80	68	83	0	10
CM3	80	68	83	0	30

†Water contents of rice straw and rice straw compost were about 10 and 75%, respectively.

replicates) for each treatment plot. The soils were air-dried and ground to 2 mm.

2.2. Soil analysis

Air-dried and ground soils were used to measure SOC and TN by standard methods according to the "Soil Normal Analysis Methods" (JSSSPN 1986). SOC and TN were analyzed by CN-900 Analyzer (Sumika Chemical Analysis Service). Mineral N [ammonium-nitrogen (NH_4^+-N) and nitrate-nitrogen (NO_3^--N)] in the air-dried soils was extracted by shaking with 10% potassium chloride (KCl) for 30 min. The extracted solutions were filtered and stored in a deep freezer (–18°C) until analysis. Both NH_4^+-N and NO_3^--N contents were measured by a colorimetric method. NH_4^+-N was measured by the nitroprusside method and NO_3^--N was measured by the hydrazine reduction method (JSSSPN 1986). The NO_3^--N contents of the soil samples were not shown in the paper, because it was not needed for calculating N mineralization.

2.3. Anaerobic incubation experiment

Each soil sample (5 g on an oven-dried basis, Purwanto *et al.* 2005) was weighed into a 68-mL serum bottle and amended with 10 mL distilled water. Each bottle was capped with a butyl rubber stopper with aluminum seal and the air inside was replaced with pure N_2 gas. All soil samples in the sealed bottles were incubated at 30ºC. After 2, 4, 6 and 8 weeks of incubation, soil samples were taken out of the incubator, to measure the CO_2 and CH_4 productions. The CO_2 and CH_4 concentrations in the headspace of each bottle were determined by gas chromatography using GC-8A and GC-2014 (Shimadzu, Kyoto, Japan) with TCD and FID detectors, respectively (Cheng *et al.* 2007). The CO_2 and CH_4 concentrations in the headspace were used to calculate CO_2 and CH_4 productions after correcting for gaseous dissolution in the incubation water by Henry's Law coefficient (Cheng *et al.* 2005). The C decomposition was estimated from the sum of CO_2 and CH_4 productions. After the gases were measured, the incubated soil was immediately extracted with 20 ml 15% KCl solution by shaking for 30 minutes on a reciprocal shaker. The amounts of NH_4^+-N in the soil extracts were measured as described above. The N mineralization was calculated as the amount of NH_4^+-N in soil after anaerobic incubation minus the amount of NH_4^+-N in air-dried soil. There was no NO_3^--N in the submerged soil under anaerobic incubation (Nishida *et al.* 2013).

2.4. Data calculations and model analyses

Since there was no plot replication for each treatment, all data from the three pseudo-replicates in this study were used only for calculating an average value for each treatment. Data for total 0–25 cm depth in all treatments was calculated from each of the five layers by arithmetic mean, while the bulk density was assumed to be the same for all layers.

Sigmaplot for Windows v. 10 was used to generate the C decomposition (CO_2 + CH_4) time curve by first-order reaction model and to estimate the C decomposition potential (*Co*) as described by the following equation:

$$Dec\ C = Co \times (1 - exp(-k_c \times t)) \quad (1)$$

where *Co* is the amount of C decomposition potential (g C kg^{-1}), k_c is the C decomposition rate constant (wk^{-1}) and *t* is incubation time (wk).

While the N mineralization time curve by first-order reaction model and for estimating the N mineralization potential (*No*) as described by the following equation:

$$Min\ N = No \times (1 - exp(-k_n \times t)) \quad (2)$$

where *No* is the amount of N mineralization potential (g N kg^{-1}), k_n is the N mineralization rate constant (wk^{-1}) and *t* is incubation time (wk).

3. Results

3.1. Changes in SOC and TN contents

All of the organic matter treatments resulted in higher SOC and TN at the 0–25 cm depth as compared to the PK and NPK treatments. Moreover, distinct differences in SOC and TN were observed among the three organic matter treatments (Fig. 1a and 2a). SOC increased by 67.3, 21.0 and 10.8% while TN increased by 64.2, 19.7 and 10.6% in CM3, RS and CM1, respectively, relative to the NPK treatment. The SOC and TN contents showed a slight reduction in the PK treatment by 5.2 and 5.7%, respectively, compared to the NPK treatment (Fig. 1a and 2a). The SOC and TN contents decreased with soil depth in all treatments (Fig. 1b and 2b). The highest SOC and

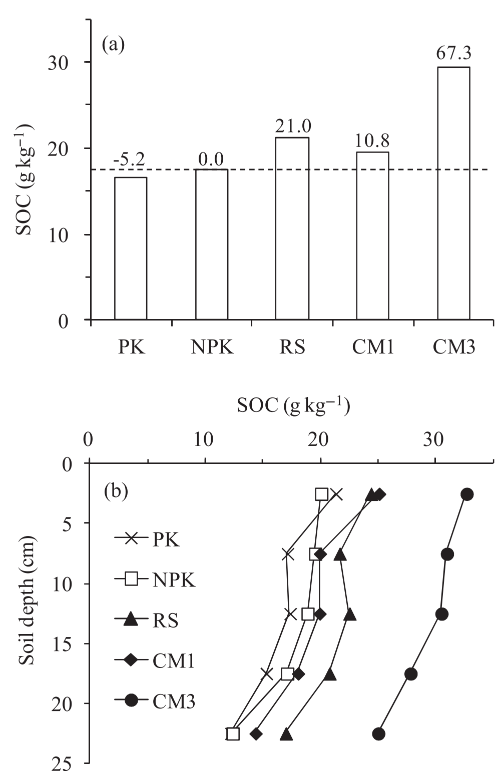

Figure 1. Long-term effects of inorganic fertilizer and organic matter treatments on soil organic carbon (SOC) contents (a) at the 0–25 cm soil depth and (b) at 5-cm soil depth increments. The numerals shown above the bars for each treatment indicate the percentage (%) changes in the SOC compared with NPK treatment (a).

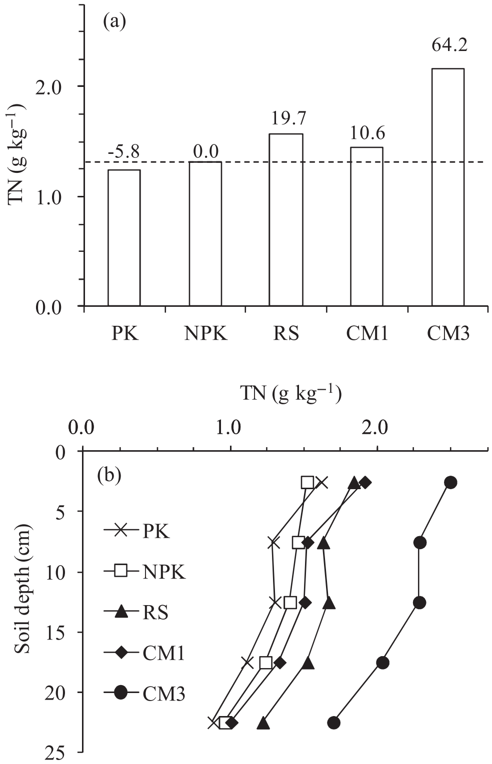

Figure 2. Long-term effects of inorganic fertilizer and organic matter treatments on total nitrogen (TN) contents (a) at the 0–25 cm soil depth and (b) at 5-cm soil depth increments. The numerals shown above the bars for each treatment indicate the percentage (%) changes in the TN compared with NPK treatment (a).

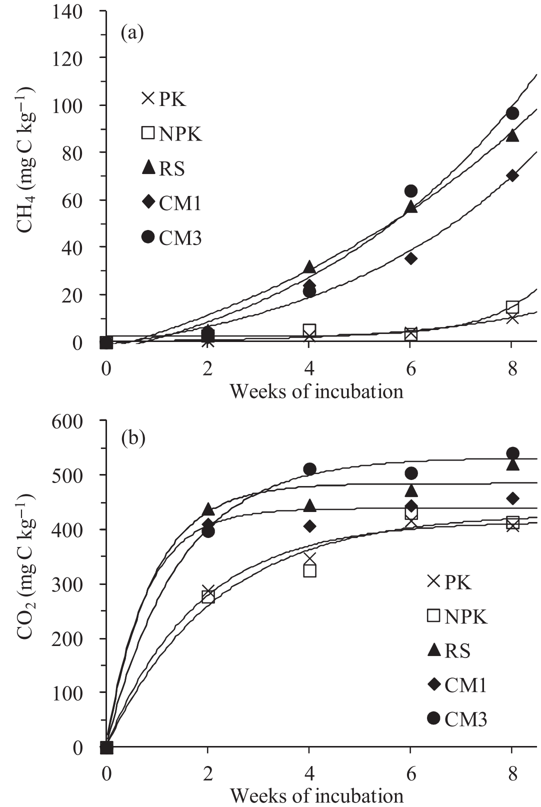

Figure 3. (a) Methane (CH_4) and (b) carbon dioxide (CO_2) productions of soils from different long-term inorganic fertilizer and organic matter treatments at the 0–25 cm soil depth, under anaerobic incubation at 30°C for 8 weeks. The CH_4 production was modeled by [$C = a + b \times exp(c \times t)$] and the CO_2 production was modeled by [$C = Co\times(1\text{-}exp(\text{-}k \times t))$].

TN contents at 0–25 cm soil depth were observed in CM3, in which rice straw compost was applied at 30 Mg ha^{-1}. The SOC and TN in the 20–25 cm layer in the CM3 treatment were even higher than the average SOC and TN contents in the 0–25 cm layer of the other treatments (Fig. 1 and 2).

3.2. CH_4 and CO_2 productions from anaerobic incubation

The CH_4 production showed an exponential increase in all treatments (Fig. 3a). Based on the average data from the five soil layers (0–25 cm) at 8 weeks, CH_4 production amounted to 10.4, 15.0, 87.6, 70.6 and 96.9 mg C kg^{-1} soil for PK, NPK, RS, CM1 and CM3 treatments, respectively. Both CM3 and RS treatments produced more CH_4 than the CM1 treatment did. The CH_4 production from all of the organic matter treatments (RS, CM1 and CM3) was obviously higher than that from the PK and NPK treatments (Fig. 3a). Applying rice straw compost at 10 Mg ha^{-1} (CM1) instead of rice straw at 6 Mg ha^{-1} (RS) to rice paddies reduced CH_4 production from the soil sampled after harvest by about 19% under 8 weeks of anaerobic incubation at 30°C.

The CO_2 production showed an exponential rise by a first-order reaction model (Fig. 3b). Based on the average CO_2 production from the five soil layers (0–25 cm) at 8 weeks, CO_2 production amounted to 407.7, 413.8, 521.5, 458.0 and 540.8 mg C kg^{-1} soil for PK, NPK, RS, CM1 and CM3 treatments, respectively. The CM3 and RS treatments obviously produced more CO_2 than the PK and NPK treatments did.

3.3. C decomposition and N mineralization potentials

The changes in C decomposition and N mineralization in the total 0–25 cm layer (Fig. 4a and b) and in each of the 5 cm soil layers (Fig. S1 and S2) were fitted very well on the first-order reaction model, but parameters of *Co* and *No*, and k_c and k_n, were different among five treatments and different depths. The amounts of *Co* and *No* were the largest in CM3 and smallest in PK or NPK treatments (Table 2).

In the total 0–25 cm layer, the C decomposition rate constant (k_c) was the largest in CM1 and smallest in NPK treatments, while the N mineralization rate constant (k_n) was the largest in CM1 and smallest in PK treatments. The ratio of k_c/k_n was the largest (1.76) in PK treatment and was smallest (0.84) in CM3 treatments (Table 2). In each of the 5 cm soil layers, the regularities of k_c, k_n and k_c/k_n were not clear; the values of k_c, k_n and k_c/k_n were around 0.30 ~ 1.43 wk^{-1}, 0.28 ~ 0.92 wk^{-1} and 0.40 ~ 1.93, respectively (Table S1).

3.4. Relationships among SOC, TN, Co and No

As expected, SOC and TN were highly correlated (Fig. 5a, P < 0.01). The C/N ratio ranged from 13.34 to 13.68 in the 0–25 cm soil depth for all treatments (Fig. S3a). The soil C/N ratios generally increased with increasing soil depth, except the sample of NPK treatment at 20–25 cm (Fig. S3b).

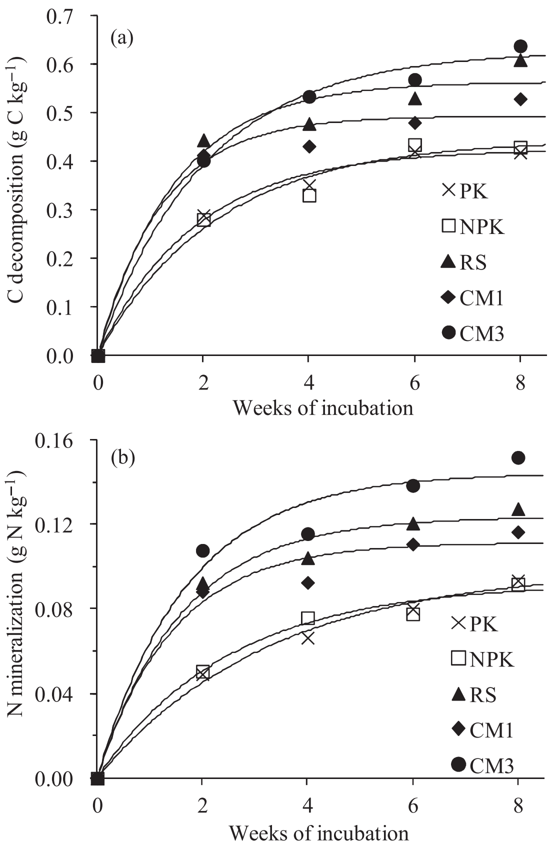

Figure 4. The changes in (a) carbon (C) decomposition and (b) nitrogen (N) mineralization in soils from different long-term inorganic fertilizer and organic matter treatments at the 0–25 cm soil depth, under anaerobic incubation at 30°C for 8 weeks. Both were modeled by [*C (or N) = Co (or No)* × *(1 − exp(−k × t)*].

Table 2. The best parameters obtained from the anaerobic incubation experiment at 30°C after 8 weeks for measuring the C decomposition potential (*Co*) and N mineralization potential (*No*) for the soil samples from different long-term inorganic fertilizer and organic matter treatments at 0–25 cm soil depth. The curves were modeled by first-order model as [*C (or N) = Co (or No)* ×*(1 − exp (−k × t)*].

	C decomposition			N mineralization				
Treatments	*Co* (g C kg^{-1})	k_c † (wk^{-1})	R^{2*}	*No* (g N kg^{-1})	k_n † (wk^{-1})	R^{2*}	*Co/No*	k_c/k_n
PK	0.424	0.532	0.993	0.099	0.303	0.991	4.28	1.76
NPK	0.443	0.442	0.982	0.092	0.398	0.990	4.82	1.11
RS	0.563	0.678	0.980	0.123	0.620	0.988	4.58	1.09
CM1	0.493	0.814	0.995	0.111	0.685	0.978	4.44	1.19
CM3	0.627	0.490	0.974	0.144	0.583	0.975	4.35	0.84

†k_c *and* k_n are the rate constants for the first-order reaction models.
* R^2 was the coefficient of determination for each model. All models were fitted significantly at $P < 0.01$.

Highly significant correlations were also found between *Co* and *No* (Fig. 5b, $P < 0.01$). The ratio of C decomposition potential and N mineralization potential (*Co/No)* was 4.49 for all treatments, and ranged from 4.28 to 4.82 among the five treatments at 0–25 cm soil depth (Table 2). The *Co/No* ratios were much lower than the total soil C/N ratios (Table 2 and Fig. S3a).

Significant linear correlations were found between *Co* and SOC and *No* and TN in all treatments, but data points from CM3 formed a different regression line with a similar slope to other treatments. It indicated that for the same amount of total SOC, a lower *Co* was obtained in CM3 than in the other treatments (Fig. 5c and 5d).

4. Discussion

4.1. *SOC and TN contents*

SOC and TN (mostly total organic N) are heterogeneous mixtures of organic substances in soil organic matter from plant photosynthesis inside or from organic matter application (Paustian *et al.* 2000; Häring *et al.* 2013). Inorganic fertilizer and organic matter application practices play a key role in the regulation of C and N contents in agricultural soils (Karlsson *et al.* 2003; Tong *et al.* 2009). Our soil analyses show that continuous rice cultivation with 10–30 Mg ha^{-1} of rice straw compost and 6 Mg ha^{-1} of rice straw, each in combination with NPK, increased soil C contents by 10.8–67.3% and 21.0%, respectively, over a period of 31 years relative to soils that received only NPK in the total 0–25 cm layer. The no-N fertilized treatment (PK) decreased SOC by 5.2% relative to the NPK treatment (Fig. 1a). Mandal *et al.* (2007) reported that long-term (7–36 years) application of organic amendments (5–10 Mg ha^{-1} yr^{-1}) through farmyard manure or compost in subtropical India could increase SOC by 10.7%, constituting 18% of the applied C. In our research, relative to the NPK treatment, SOC increased by 10.8% in the CM1 treatment, similar to what Mandal *et al.* (2007) reported. However, the SOC increased 6.3 times more in CM3 (67.3%) than in CM1 (10.8%), though the application rate of rice straw compost was only 3 times higher in CM3 than in CM1. This indicates that application of 30 Mg ha^{-1} rice straw compost every year accelerated SOC sequestration compared to the local conventional application at 10 Mg ha^{-1} in the cold temperate region of Yamagata, Japan. The changes in soil TN contents usually were determined by the balance of N application from inorganic fertilizers and organic matter, and absorption by the crop aboveground biomass in an agroecosystem. But the input from N fixation and irrigation water and output from denitrification also control the N balance and storage in the rice paddy (Koyama and App 1979; Nishida *et al.* 2007; Nishida and Sato 2016). Our soil analyses show that continuous rice cultivation with 10–30 Mg ha^{-1} of rice straw compost and 6 Mg ha^{-1} of rice straw, each in combination with NPK, increased TN contents by 10.6–64.2% and 19.7%, respectively, over a period of 31 years relative to soils that received only NPK. The no-N fertilized treatment (PK) decreased TN by 5.8% relative to the NPK treatment (Fig. 2b). Changes in SOC and TN contents resulting in quite similar C/N ratios (13.34 ~ 13.68) in the long-term experiment imply that SOC sequestration could not happen without N enrichment in the rice paddy ecosystems.

4.2. *CH_4 production*

Increasing the C content of agricultural lands through organic matter application can mitigate global warming by reducing CO_2 emissions. However, after CO_2, CH_4 is the most important greenhouse gas, responsible for approximately 20% of the anthropogenic global warming effect. The global warming

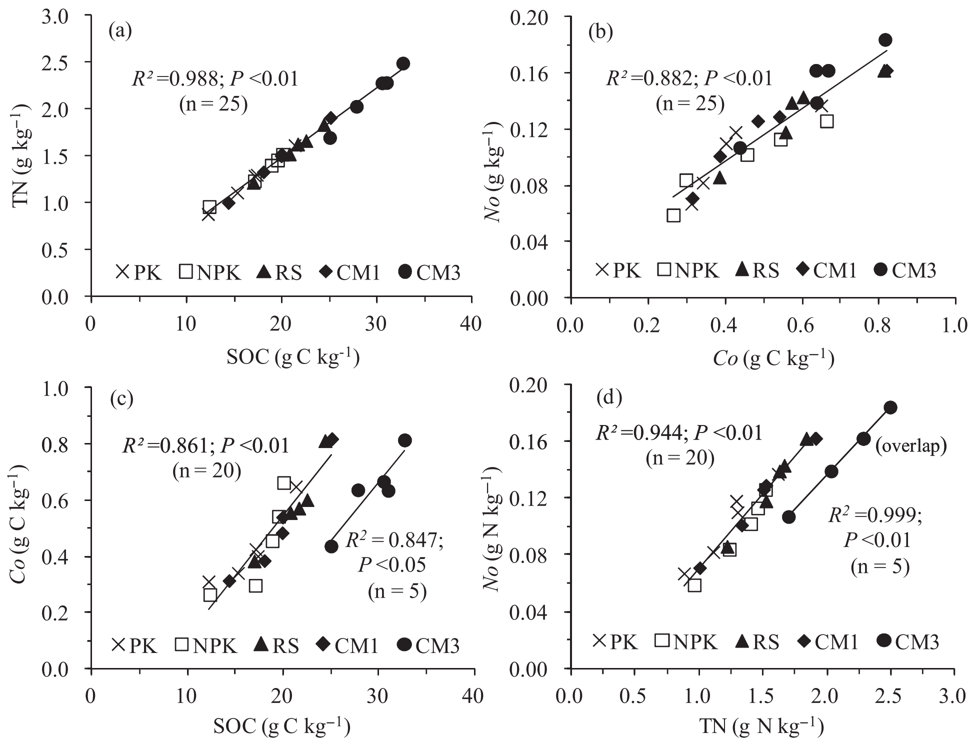

Figure 5. The relationship between (a) soil organic carbon (SOC) and total nitrogen (TN), (b) carbon (C) decomposition potential (*Co*) and nitrogen (N) mineralization potential (*No*), (c) SOC and *Co*, and (d) TN and *No*, in the soils from different long-term inorganic fertilizer and organic matter treatments in the five layers. The coefficient of determination (R^2) and *P* value are shown in each plot.

potential of CH_4 is 25 times that of CO_2 over a 100-year time horizon (IPCC 2007). Different from the uplands, the soil decomposable C in a submerged rice paddy is not only mineralized to CO_2, but also fermented to CH_4 after the electron acceptors in soil, such as NO_3^-, Mn(IV), Fe(III) and SO_4^{2-}, have been completely reduced (Takai 1970; Patrick and DeLaune 1972; Cheng *et al.* 2007). It is important to estimate the CH_4 production of organic matter applied to rice paddies (Yagi *et al.* 1997). Our results show that CH_4 production was higher from organic matter treatments (RS, CM1 and CM3) than from the NPK and PK treatments (Fig. 3a). Therefore, when evaluating the C sequestration in rice paddies, from organic matter application, the CH_4 production and emission during the flooded rice growth season must also be considered. Though we did not measure the CH_4 emissions during the rice growth season from all treatment plots directly, the CH_4 production from the soil sampled after harvest also can be an index to show CH_4 emission potential from soil organic matter. The application of a high rate of rice straw compost (30 Mg ha^{-1}) in this LTE showed a higher CH_4 production after 8 weeks' incubation than the rice straw treatment at 6 Mg ha^{-1} did (Fig. 3a). This result may imply that the CH_4 emission from the source of SOC during the rice growth season (not the source of organic matter applied in same season) would be larger in the soil from the high rate of rice straw compost (30 Mg ha^{-1}) treatment than that of rice straw (6 Mg ha^{-1}). However, applying rice straw compost at 10 Mg ha^{-1} (CM1) instead of rice straw at 6 Mg ha^{-1} (RS) to rice paddies can reduce CH_4 production by about 19%.

4.3. Soil C decomposition and N mineralization

C decomposition and N mineralization were measured simultaneously by anaerobic incubation experiment during 8 weeks at 30°C in this study. The decomposable C and mineralizable N are the active fractions of soil organic matter. Our data show that there was also a highly significant linear relationship between the C decomposition potential (*Co*) and N mineralization potential (*No*) modeled by the first-order reaction model from 8 weeks' anaerobic incubation (Fig. 4a and b). The mean ratio of *Co* to *No* (*Co/No*) was 4.49 in all treatments, and around 4.28 ~ 4.82 (Table 2), which is close to soil microbial biomass C and N ratio in a Gley rice paddy soil reported by Shibahara and Inubushi (1995), and close to the decomposed C and N ratio in uplands (Moriizumi *et al.* 2015). Compared to the total SOC/TN (13.34 ~ 13.68; Fig. S3a), the ratio of *Co* to *No* was lower than that of the bulk soil organic matter pool, which indicated that the easily decomposed organic matter was from soil microbial biomass and soil protein (Rillig *et al.* 2007; Moriizumi *et al.* 2015). This result is consistent with our previous report (Cheng *et al.* 2007). On the other hand, the correlations between *Co* and SOC or between *No* and TN could be divided into two groups: the CM3 treatment, and the others (PK, NPK, RS and CM1) (Fig. 5c and d). The different regression lines with the lower y intercept from CM3 compared to the other treatments means that the percentage of easily decomposable organic matter in total soil organic matter was lower in the CM3 treatment than in the other treatments.

Many papers have reported the N mineralization process in submerged paddy soils by single or double first-order reaction models (Inubushi *et al.* 1985; Sugihara *et al.* 1986; Ando *et al.* 1992; Watanabe *et al.* 1996; Purwanto *et al.* 2005). However, only a few papers have reported using the first-order reaction model to estimate C decomposition and N mineralization processes in uplands. To our knowledge, there has been no published report showing the simultaneous estimation of C decomposition and N mineralization processes by first-order reaction models in submerged paddy soils, especially for a long-term temperate rice paddy experiment. In the first-order reaction model, the large C decomposition or N mineralization rate constants (k_c or k_n) represented quick reaction processes for C decomposition or N mineralization. Though the regularities of k_c, k_n and k_c/k_n were not clear in each of the 5 cm soil layers (Fig. S1 and S2; Table S1), the values of k_c, k_n and k_c/k_n for the total 0–25 cm layer obviously showed that k_c/k_n were similar at 1.09 ~ 1.19 among NPK, RS and CM1 treatments (Table 2). This implies that the processes of C decomposition and N mineralization were synchronous and their respective rates were similar in NPK, RS and CM1 treatments. The highest k_c/k_n (1.76) in the PK treatment implies that the process of C decomposition was quicker than that of N mineralization, while the lowest k_c/k_n (0.84) in the CM3 treatment implies that the process of C decomposition was slower than that of N mineralization. This could be due to the absence of N fertilizer in the PK treatment, and extra amounts of rice straw compost (30 Mg ha^{-1}) application in the CM3 treatment (Table 2).

5. Conclusions

Changes in SOC and TN contents, C decomposition and N mineralization potentials were obviously observed after 31 years of organic matter applications with reference to NPK-fertilized rice paddy soils. The highest increases in SOC and TN contents were observed with the application of 30 Mg ha^{-1} rice straw compost, followed by 6 Mg ha^{-1} rice straw, then 10 Mg ha^{-1} rice straw compost. There was a highly significant linear relationship not only between SOC and TN, but also between the C decomposition and N mineralization potentials. The primary data generated from this study could provide essential information on optimizing rates of organic matter application for sustaining soil fertility, and for modeling C and N dynamics in paddy rice systems.

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