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Decomposition of soil organic carbon influenced by soil temperature and moisture in Andisol and Inceptisol paddy soils in a cold temperate region of Japan

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Abstract

Purpose Understanding the effects of temperature and moisture on soil organic carbon (SOC) dynamics is crucial to predict the cycling of C in terrestrial ecosystems under a changing climate. For single rice cropping system, there are two contrasting phases of SOC decomposition in rice paddy soils: mineralization under aerobic conditions during the off-rice season and fermentation under anaerobic conditions during the growth season. This study aimed to investigate the effects of soil temperature and moisture on SOC decomposition under the aerobic and subsequently anaerobic conditions.

Materials and methods Two Japanese paddy soils (Andisol and Inceptisol) were firstly incubated under four temperatures (±5, 5, 15, and 25°C) and two moisture levels (60 and 100% water-filled pore space (WFPS)) under aerobic conditions for 24 weeks. Then, these samples were incubated for 4 weeks at 30°C and under anaerobic conditions. Carbon dioxide (CO_2) and methane (CH_4) productions were measured during the two incubation stages to monitor the SOC decomposition dynamics. The temperature sensitivity of SOC was estimated by calculation of the Q_{10} parameter.

Results and discussion The total CO_2 production after the 24-week aerobic incubation was significantly higher in both soils for increasing soil temperature and moisture ($P < 0.01$). During the subsequent anaerobic incubation, total decomposed C (sum of CO_2 and CH_4 productions) was significantly lower in samples that had been aerobically incubated at higher temperatures (15 and 25°C). Moreover, CH_4 production was extremely low in all soil samples. Total decomposed C after the two incubation stages ranged from 256.8 to 1146.1 mg C kg^{-1} in the Andisol and from 301.3 to 668.8 mg C kg^{-1} in the Inceptisol. However, the ratios of total decomposed C to SOC ranged from 0.29 to 1.29% in the Andisol and from 2.21 to 4.91% in the Inceptisol.

Conclusions Both aerobic and anaerobic decompositions of SOC in two paddy soils were significantly affected by soil temperature and moisture. Maintaining optimal soil temperature and medium moisture during the off-rice season might be an appropriate agricultural management to mitigate CH_4 emission in the following rice growth season. Although it is high in SOC content, Andisol has less biodegradable components compared to Inceptisol and this could be a probable reason for the distinct difference in temperature sensitivity of SOC decomposition between two paddy soils.

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1 Introduction

Soils store twice as much carbon (C) as the atmosphere and about four times as much as plant biomass (Batjes 1996; Collins et al. 2013). The changes in stock of soil organic C (SOC) in terrestrial ecosystems in response to climate change depend on the balance between C inputs to soil by net primary production and C outputs into the atmosphere by SOC decomposition (Davidson and Janssens 2006; von Lützow and Kögel-Knabner 2009). A small change in soil respiration resulting from natural processes or anthropogenic activities could significantly intensify or mitigate atmospheric carbon dioxide (CO_2) emission (Baveye 2007; Smith et al. 2008). Soil temperature and moisture have been identified as two key environmental factors regulating the decomposition of SOC in agroecosystems (Davidson and Janssens 2006; Xu et al. 2012; Zhou et al. 2014b; Huang et al. 2016). An increase in soil temperature accelerates SOC decomposition because temperature-dependent reactions performed by microorganisms result in more rapid CO_2 emissions from soil to the atmosphere (Trumbore and Czimczik 2008; Karhu et al. 2014). Soil moisture can have a great impact on SOC decomposition by affecting the oxygen diffusion into the soil and the substrate availability for soil microorganisms (Linn and Doran 1984; Suseela et al. 2012; Wang et al. 2014; Zhou et al. 2014b; Sierra et al. 2015). Many studies about the response of SOC decomposition to temperature change are mainly conducted in forest, grassland, and upland ecosystems (Luo et al. 2001; Conen et al. 2006; Vanhala et al. 2007; He et al. 2013; Zhou et al. 2014b; Xu et al. 2016a). However, relatively few studies have examined the combined effects of soil temperature and moisture on SOC decomposition in paddy soils.

Rice paddies account for a large fraction of the wetland ecosystem with most of them in Asian countries. Single rice cropping is a common system in cold temperate regions like the northeastern Japan where there is a long snow cover period during the winter season (Figs. S1, S2, and S3, Electronic Supplementary Material). The Andisols and Inceptisols are commonly used for rice cultivation in Japan (Shoji et al. 1994; Cheng et al. 2007). Andisols are characterized by specific physicochemical properties like low bulk density, high SOC content, high porosity, and stable soil aggregates (Shoji et al. 1994; Dorel et al. 2000; Hoyos and Comeford 2005). On the other hand, Inceptisols are considered as the most widely distributed soils, which were formed through the alteration of parent material. They are characterized by weak pedogenesis,

no accumulation of clays, low cation exchange capacity, and poor soil fertility (Foss et al. 1983). Besides, the chemical recalcitrance, the formation of organo-mineral associations, resulting in the physical protection of the soil organic matter, has been reported as a major process for C stability in soils (Saggar et al. 1996; Müller and Höper 2004; Davidson and Janssens 2006). For example, Frøseth and Bleken (2015) studied SOC decomposition in a clay soil and a sandy soil at low temperature (0–15°C) and found that temperature sensitivity of SOC was the same in both soils although SOC decomposition was twice as fast in the sandy soil as in the clay soil. On the basis of evident differences in physical and chemical properties between Andisol and Inceptisol, the response of SOC decomposition to soil temperature and moisture might vary between these two soils.

In northeastern Japan (Fig. S1, Electronic Supplementary Material), the single rice is generally grown from early May to mid-October under mostly submerged soil conditions throughout the rice growth season. There are two short periods of drainage conducted in middle of rice growth before booting stage (about 1 week) and grain-filling stage (about 2 weeks prior to harvest). The rice paddies are then left under aerobic conditions for the off-rice season, usually lasting from late October to late April (Nakajima et al. 2016). Due to the low soil temperatures as a result of the long winter season with heavy snow (Figs. S2 and S3, Electronic Supplementary Material), the decomposition of SOC is slow during the off-rice season and a considerable amount remains in the soil at the beginning of the subsequent rice growth season. However, it is still not fully understood whether the undecomposed SOC during the off-rice season will lead to a remarkable CH_4 production in the following rice growth season. Therefore, we conducted an incubation experiment to simulate the effects of soil temperature and moisture during rice off season on SOC decomposition in two contrasting paddy soils. The objectives of this study were (1) to investigate the effects of soil temperature and moisture conditions during the off-rice season on SOC decomposition in Andisol and Inceptisol rice paddy soils, and (2) to compare the SOC decomposition between these two soils during both aerobic and anaerobic incubations.

2 Material and methods

2.1 Soil sampling and pre-incubation

Soil samples were taken from 0- to 10-cm depth at NARO Tohoku Agricultural Research Center (39°42′ N, 141°09′ E), Iwate Prefecture, and from 0- to 15-cm depth at Yamagata Integrated Agricultural Research Center (38°16′ N, 140°19′ E), Yamagata Prefecture, Japan. Both sites are located in northeastern Japan (Fig. S1, Electronic

Supplementary Material). The samples from Iwate and Yamagata were respectively classified as Andisol and Inceptisol (Soil Survey Staff 1999). The two samples are typical rice paddy soils in cold temperate regions of northeastern Japan. The Andisol soil contained 89.0 g kg^{-1} SOC, 6.7 g kg^{-1} total nitrogen (TN), and a pH of 5.8. While the Inceptisol soil contained 13.6 g kg^{-1} SOC, 1.2 g kg^{-1} TN, and a pH of 5.5. After the manual removal of the visible roots and small stones, soil samples were air dried, sieved through a 2 mm sieve, and stored at room temperature.

Before the aerobic incubation experiment, soil samples were pre-incubated at 25°C for 4 weeks in the dark to restore microbial activity. The moisture was maintained at 40% water-filled pore space (WFPS) by periodic addition of deionized water. The WFPS was calculated from Eq. (1):

$$WFPS = \frac{\theta_V}{1-\left(\frac{BD}{PD}\right)} \times 100 \tag{1}$$

where θ_v, BD, and PD are volumetric soil moisture, soil bulk density, and soil particle density (2.65 g cm^{-3} as a fixed constant), respectively (Aulakh et al. 1991; Cheng et al. 2004).

2.2 Aerobic incubation

Based on temperature and moisture conditions during the off-rice season in northeastern Japan, an aerobic incubation experiment was conducted under four temperature levels (−5 to 5 (noted by ±5), 5, 15, 25°C) and two moisture levels (60 and 100% WFPS; abbreviated L and H). Temperature level at ±5°C was used to simulate diurnal variation of soil temperature between night (−5°C, 12 h) and day (5°C, 12 h) and the corresponding freeze-thaw cycles occurring during the off-rice season. Hence, there were eight treatments in this experiment, namely L ± 5, L5, L15, L25, H ± 5, H5, H15, and H25.

After the 4-week pre-incubation, 5-g subsamples (dry-weight basis) were placed into 68-mL serum bottles (total 48 samples). Soil moisture in half of serum bottles were adjusted to 60 and 100% WFPS, respectively, by adding deionized water with a mini-pipette. Then, all serum bottles were purged with pure air (80% N$_2$ + 20% O$_2$) and capped with a butyl rubber stopper with aluminum seal. At the interval of every 2 weeks through the incubation, the headspace of each serum bottle was sampled to measure CO$_2$ and CH$_4$ by gas chromatography (GC-8A; Shimadzu, Kyoto, Japan) equipped with thermal conductivity detector (TCD) and flame ionization detector (FID). After each gas sampling, the headspace was purged with pure air and the butyl rubber stopper and aluminum seal were replaced with new ones.

2.3 Anaerobic incubation

After the 24-week aerobic incubation, all soil samples in the serum bottles were submerged with 10 ml of deionized water, purged with pure N$_2$ gas for 5 min and capped with a butyl rubber stopper and an aluminum seal. They were later incubated at 30°C for 4 weeks. Then, the difference we aim to investigate between our samples during this anaerobic incubation will only be derived from the effect of temperature and moisture during the precedent aerobic incubation step. The three replicates within each treatment were used for measuring the headspace concentrations of CO$_2$ and CH$_4$ as same as for the aerobic incubation.

2.4 Calculation of Q$_{10}$ and statistical analysis

In our study, the temperature coefficient (Q$_{10}$) was calculated to assess the increase in cumulative CO$_2$ production as a result of a temperature increase of 10°C during the 24-week aerobic incubation. It was calculated from Eq. (2):

$$Q_{10} = (k_2/k_1)^{10/(T_2-T_1)} \tag{2}$$

where k is the cumulative CO$_2$ production in aerobic incubation and T is the temperature level of ±5, 5, 15, and 25°C, respectively. The average temperature change at ±5°C is regarded as 0°C.

Two-way analyses of variance (ANOVA) were performed to evaluate the effects of temperature, moisture, and their interaction on CO$_2$ and CH$_4$ productions, total decomposed C, and the ratios of total decomposed C to SOC for the two soils. The statistical analysis was computed using SPSS statistics version 21 (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 CO$_2$ production during the aerobic incubation

The cumulative CO$_2$ productions during the 24-week incubation in the Andisol and Inceptisol are shown in Fig. 1a, b. The cumulative CO$_2$ production increased with temperature for both soil samples. The total CO$_2$ productions ranged from 72.2 to 1018.6 mg C kg^{-1} in the Andisol and from 64.9 to 599.8 mg C kg^{-1} in the Inceptisol, respectively (Table 1). Soil temperature and moisture had positive effects on CO$_2$ production in both soil samples (Table 1, $P < 0.01$). For the same temperature and moisture conditions, the cumulative CO$_2$ productions in the Andisol were always higher than in the Inceptisol. However, at low temperatures, the difference between the two soils was not as distinct as that at high temperatures (15 and 25°C). Besides, an interactive effect of soil temperature and moisture was observed for both soils.
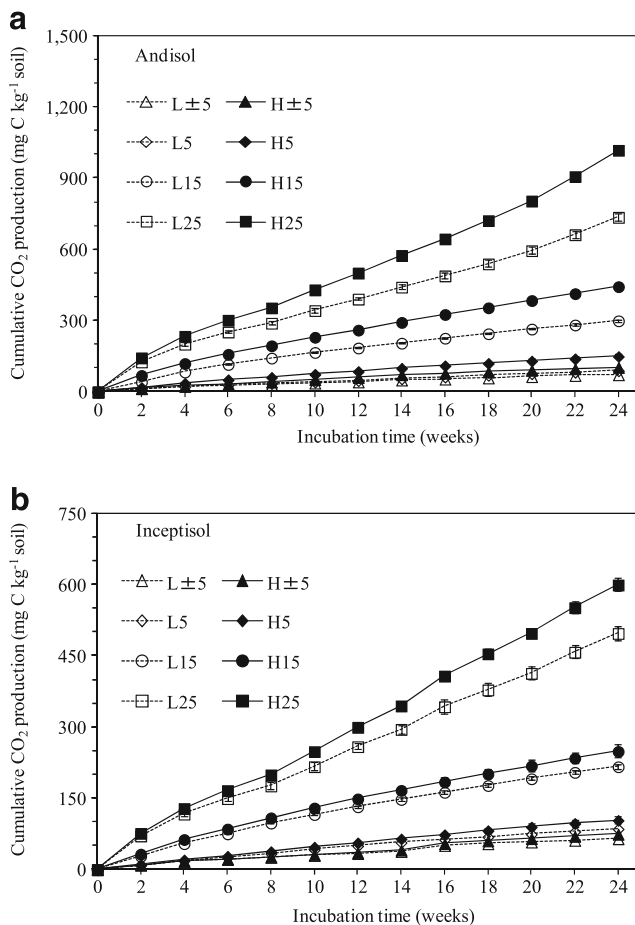
Fig. 1 Cumulative CO_2 production from Andisol (**a**) and Inceptisol (**b**) soil samples during the 24-week aerobic incubation under four temperature (±5, 5, 15, and 25°C) and two moisture (60 and 100% WFPS) conditions. Low (60% WFPS) and high (100% WFPS) moistures are abbreviated to L and H, respectively

3.2 CO_2 and CH_4 productions during the anaerobic incubation

During the 4-week anaerobic incubation, the temperature and moisture conditions were strictly the same for all samples (30°C and submerged conditions). Then, the measured differences resulted from the effect applied during the previous aerobic incubation phase. In the following sections, we named previous temperature and previous moisture conditions during the aerobic phase of the incubation. The CO_2 and CH_4 productions during the 4-week anaerobic incubation are shown in Table 2. The CO_2 production ranged from 124.1 to 184.6 mg C kg^{-1} in the Andisol and from 68.9 to 248.1 mg C kg^{-1} in the Inceptisol. The CO_2 production in both soil samples was higher for previous temperatures of ±5 and 5°C and lower for previous temperatures of 15 and 25°C. The difference in CO_2 production between ±5 and 25°C for previous temperature treatment was larger in the Inceptisol than in the Andisol soil samples. A significant effect of

previous temperature on CO_2 production was found for each soil (Table 2, $P < 0.01$). The CH_4 production ranged from 7.4 to 110.8 µg C kg^{-1} in the Andisol and from 9.0 to 243.9 µg C kg^{-1} in the Inceptisol. The CH_4 productions were distinctly lower than CO_2 production for both soil samples. There was no significant effect of previous soil moisture condition on CO_2 and CH_4 production during the 4-week anaerobic incubation (Table 2).

3.3 Total decomposed C and the ratios of total decomposed C to SOC

The total decomposed C at the end of the whole incubation ranged from 256.9 to 1146.1 mg C kg^{-1} in the Andisol and from 301.3 to 668.8 mg C kg^{-1} in the Inceptisol. Under low temperature conditions (±5 and 5°C), the total decomposed C was higher for the Inceptisol than for the Andisol, while the situation was inverted under high temperature conditions (15 and 25°C) (Table 1). Both the previous soil temperature and moisture had significant effects on total decomposed C for each soil. The ratios of anaerobically decomposed C (CO_2-C + CH_4-C) to total decomposed C varied from 11.1 to 71.9% in the Andisol and from 10.3 to 79.2% in the Inceptisol (Table 3). Moreover, for the two soils, the ratios of anaerobically decomposed C to total decomposed C decreased with the increases of previous soil temperature and moisture treatments (Table 3). The ratios of anaerobically decomposed C to SOC varied from 0.14 to 0.21% in the Andisol and from 0.51 to 1.82% in the Inceptisol, respectively. Only the effect of previous temperature treatments on the ratios of anaerobically decomposed C to SOC was found significant for both soil samples (Table 3). Total decomposed C/SOC ranged from 2.21 to 4.91% in Inceptisol, clearly higher than that in the Andisol with values ranging from 0.29 to 1.29%. The effect of previous soil temperature and moisture, and their interaction on total decomposed C/SOC were significant for both soils (Table 3).

3.4 Changes in the Q_{10} of aerobic decomposition of SOC

The changes in Q_{10} values for the Andisol and the Inceptisol during the 24-week aerobic incubation are shown in Fig. 2. The Q_{10} values between 5 and 15°C were always larger than those between 15 to 25 and ±5 to 5°C in both soil samples. The Q_{10} values were larger under low moisture condition than those under high moisture between 5 and 15°C in the Andisol. Nevertheless, the Q_{10} values were smaller under low moisture condition than those under high moisture between ±5 and 5°C in both soil samples (Fig. 2). The mean Q_{10} values of SOC decomposition rates under the four temperature and two moisture treatments calculated from 12 times data during the 24-week aerobic incubation are shown in Table 4. The averaged Q_{10} value in two soils was highest at 5 to 15°C temperature increase, and lowest at ±5 to 5°C temperature changes.

Table 1 The cumulative CO_2 productions during the 24-week aerobic incubation under four temperature and two moisture conditions, CO_2 and CH_4 productions ($CO_2 + CH_4$) during the subsequent 4-week anaerobic incubation at 30°C under submerged conditions, and the total decomposed C during both aerobic and anaerobic incubations of Andisol and Inceptisol soil samples, respectively

Temperature	Moisture (WFPS)	Code	Aerobic incubation (CO_2) (mg C kg^{-1})		Anaerobic incubation ($CO_2 + CH_4$) (mg C kg^{-1})		Total decomposed C ($CO_2 + CH_4$) (mg C kg^{-1})	
			Andisol	Inceptisol	Andisol	Inceptisol	Andisol	Inceptisol
±5°C	60%	L ± 5	72.2 ± 6.3	64.9 ± 3.4	184.7 ± 4.7	248.3 ± 21.0	256.9 ± 6.1	313.2 ± 21.2
	100%	H ± 5	103.3 ± 1.6	74.5 ± 4.6	177.5 ± 7.4	226.8 ± 4.8	280.8 ± 9.0	301.3 ± 9.4
5°C	60%	L5	89.1 ± 4.9	85.6 ± 4.4	174.5 ± 6.5	238.7 ± 18.9	263.6 ± 11.3	324.2 ± 19.1
	100%	H5	149.5 ± 2.9	103.7 ± 7.7	165.6 ± 14.1	233.9 ± 22.9	315.1 ± 16.4	337.7 ± 27.5
15°C	60%	L15	299.8 ± 9.1	216.8 ± 4.7	139.6 ± 2.0	98.0 ± 0.4	439.4 ± 8.2	314.8 ± 5.1
	100%	H15	443.8 ± 28.4	249.0 ± 13.1	144.5 ± 17.5	87.5 ± 1.8	588.3 ± 34.2	336.5 ± 14.3
25°C	60%	L25	736.0 ± 15.9	497.6 ± 14.7	124.1 ± 2.1	76.7 ± 1.9	860.1 ± 17.8	574.4 ± 12.9
	100%	H25	1018.6 ± 12.7	599.8 ± 14.0	127.5 ± 0.8	69.0 ± 1.9	1146.1 ± 13.4	668.8 ± 12.9
ANOVA results (P value)								
Temperature			<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Moisture			<0.01	<0.01	0.60	0.05	<0.01	<0.01
Temperature × moisture			<0.01	<0.01	0.44	0.71	<0.01	0.06

Each data was presented as mean and standard deviation ($n = 3$). The P values were obtained from the two-way ANOVA for the effects of temperature, moisture, and their interaction on each tested parameter

4 Discussion

4.1 Effects of temperature and moisture on aerobic decomposition of SOC

In this study, we simulated various climatic conditions (four temperature and two moisture conditions) for the off-rice season in the cold temperate region of northeastern Japan, in order to study the effect of temperature and moisture on SOC decomposition. The cumulative CO_2 production in both soil samples increased distinctly with the increase of soil temperature during the 24-week aerobic incubation (Fig. 1 and Table 1). This result was consistent with Zhou et al. (2014a) who incubated three paddy soils at five temperatures (10, 15, 20, 25, and 30°C) and 90% water content for 160 days. The positive feedback of SOC decomposition to increasing

Table 2 The CO_2 and CH_4 productions from Andisol and Inceptisol soil samples during the 4-week anaerobic incubation at 30°C and under submerged conditions

Temperature	Moisture (WFPS)	Code	CO_2 production (mg C kg^{-1})		CH_4 production (μg C kg^{-1})	
			Andisol	Inceptisol	Andisol	Inceptisol
±5°C	60%	L ± 5	184.6 ± 4.8	248.1 ± 21.0	99.9 ± 58.2	192.4 ± 21.6
	100%	H ± 5	177.4 ± 7.4	226.6 ± 4.8	74.2 ± 21.6	243.9 ± 14.6
5°C	60%	L5	174.3 ± 6.5	238.5 ± 18.9	110.8 ± 77.2	170.6 ± 31.0
	100%	H5	165.5 ± 14.1	233.8 ± 22.9	70.3 ± 25.5	154.0 ± 0.0
15°C	60%	L15	139.6 ± 2.0	98.0 ± 0.4	15.6 ± 4.5	21.6 ± 12.2
	100%	H15	144.5 ± 17.5	87.5 ± 1.8	7.4 ± 0.8	11.6 ± 1.6
25°C	60%	L25	124.1 ± 2.1	76.7 ± 1.9	7.8 ± 2.0	15. 9 ± 6.0
	100%	H25	127.5 ± 0.8	68.9 ± 1,9	8.8 ± 4.1	9.0 ± 1.3
ANOVA results (P value)						
Temperature			<0.01	<0.01	<0.01	<0.01
Moisture			0.60	0.05	0.23	0.47
Temperature × moisture			0.44	0.71	0.76	<0.01

Each data was presented as mean and standard deviation ($n = 3$). The P values were obtained from the two-way ANOVA for the effects of temperature, moisture, and their interaction on each tested parameter

Table 3 Ratios of anaerobically decomposed C to total decomposed C (aerobic + anaerobic), anaerobically decomposed C to soil organic C (SOC), and total decomposed C to SOC in Andisol and Inceptisol soil samples, respectively

Temperature	Moisture (WFPS)	Code	Anaerobic decomposed C/total decomposed C		Anaerobic decomposed C/SOC		Total decomposed C/SOC	
			(%)		(%)		(%)	
			Andisol	Inceptisol	Andisol	Inceptisol	Andisol	Inceptisol
±5°C	60%	L ± 5	71.9 ± 2.0	79.2 ± 1.6	0.21 ± 0.01	1.82 ± 0.15	0.29 ± 0.01	2.30 ± 0.16
	100%	H ± 5	63.2 ± 0.6	75.3 ± 0.8	0.20 ± 0.01	1.67 ± 0.04	0.32 ± 0.01	2.21 ± 0.07
5°C	60%	L5	66.2 ± 0.5	73.6 ± 1.9	0.20 ± 0.01	1.75 ± 0.17	0.30 ± 0.01	2.38 ± 0.14
	100%	H5	52.5 ± 1.7	69.2 ± 1.9	0.19 ± 0.02	1.72 ± 0.00	0.35 ± 0.02	2.48 ± 0.20
15°C	60%	L15	31.8 ± 0.9	31.1 ± 0.4	0.16 ± 0.00	0.72 ± 0.01	0.49 ± 0.01	2.31 ± 0.04
	100%	H15	24.6 ± 2.4	26.0 ± 0.8	0.16 ± 0.02	0.64 ± 0.01	0.66 ± 0.04	2.47 ± 0.11
25°C	60%	L25	14.4 ± 0.1	13.4 ± 0.6	0.14 ± 0.00	0.56 ± 0.01	0.97 ± 0.02	4.22 ± 0.09
	100%	H25	11.1 ± 0.1	10.3 ± 0.4	0.14 ± 0.00	0.51 ± 0.01	1.29 ± 0.02	4.91 ± 0.09
ANOVA results (P value)								
Temperature			<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Moisture			<0.01	<0.01	0.60	0.05	<0.01	<0.01
Temperature × moisture			<0.01	<0.53	0.44	0.71	<0.01	<0.01

Each data was presented as mean and standard deviation (n = 3). The P values were obtained from the two-way ANOVA for the effects of temperature, moisture, and their interaction on each tested parameter

temperature should be attributed to the acceleration of microbial activities and uptake of soluble substrates resulting in increased soil respiration rates. Several studies reported that soil moisture has a significant impact on SOC decomposition mainly by affecting substrate availability and oxygen diffusion (Linn and Doran 1984; Suseela et al. 2012; Wang et al. 2014; Zhou et al. 2014b; Sierra et al. 2015). The optimum soil moisture for SOC decomposition was usually found at intermediate level, e.g., 60%WFPS (Linn and Doran 1984; Oberbauer et al. 1992; Jassal et al. 2008). However, in this study, the cumulative CO_2 productions were higher at high moisture (100% WFPS) than those at low moisture (60% WFPS) (Fig. 1). The CO_2 production was not limited by high moisture in this study. This result may be due to enough oxygen availability by the shallow soil layer (about 1 cm) and to the more soluble substrate for microbial activities.

The parameter Q_{10} is usually used to predict the response of SOC decomposition and sequestration in terrestrial ecosystems to future warming temperature (Fang et al. 2005; Xu et al. 2010; He et al. 2013; Zhou et al. 2014b). The mean values of Q_{10} for SOC decomposition as cumulative CO_2 production from the Andisol and the Inceptisol computed from 12 times data during the 24-week aerobic incubation ranged from 1.7 to 2.4 in Inceptisol and from 1.5 to 3.4 in Andisol, respectively (Table 4). For the both soils, the highest Q_{10} was found under low moisture (60% WFPS) between 5 and 15°C (L5/15) and lowest at low moisture between ±5 and 5°C (L ± 5/5) (Fig. 2 and Table 4). Moreover, the Andisol had higher Q_{10} than the Inceptisol at the temperature change from 5 and 15°C under the two moisture regimes. This finding

indicates that the decomposition of SOC in Andisol was more sensitive to temperature increase from 5 to 15°C. Temperature at ±5°C was used to simulate the freeze-thaw cycles during off-rice season in this study. Soil moisture only enhanced the Q_{10} at the temperature increase from ±5 to 5°C in the Andisol and the Inceptisol. This result indicates that the freeze-thaw cycles enhanced the microbial activities at high moisture than that at low moisture. Previous studies have shown that freeze-thaw cycles could affect soil and plant residues decomposition, resulting in great changes in C cycles in terrestrial ecosystems mainly owing to the increase of nutrient availability (Yanai et al. 2004; Xu et al. 2016b). However, in our study, the total CO_2 productions in both soil samples at ±5°C were lower than those at 5°C. It could be attributed to relatively small temperature change between ±5 and 5°C compared with those in previous studies (Yanai et al. 2004; Xu et al. 2016b).

4.2 CH4 production during the anaerobic incubation

The decomposition of SOC in flooded paddy soils is different from that of aerobic soils because under submerged conditions and at low redox potential, a significant fraction of SOC is fermented to CH_4 during rice growth season with high temperature and anaerobic condition (Kimura et al. 2004). Here, the rice growth season is simulated by the 4-week anaerobic incubation at 30°C and under submerged conditions. Compared with CO_2 production (more than 68.9 mg C kg^{-1}) during the 4-week anaerobic incubation, the CH_4 productions were very low (less than 243.9 μg C kg^{-1}) in all soil samples (Table 2). Furthermore, anaerobic CH_4 productions in soil
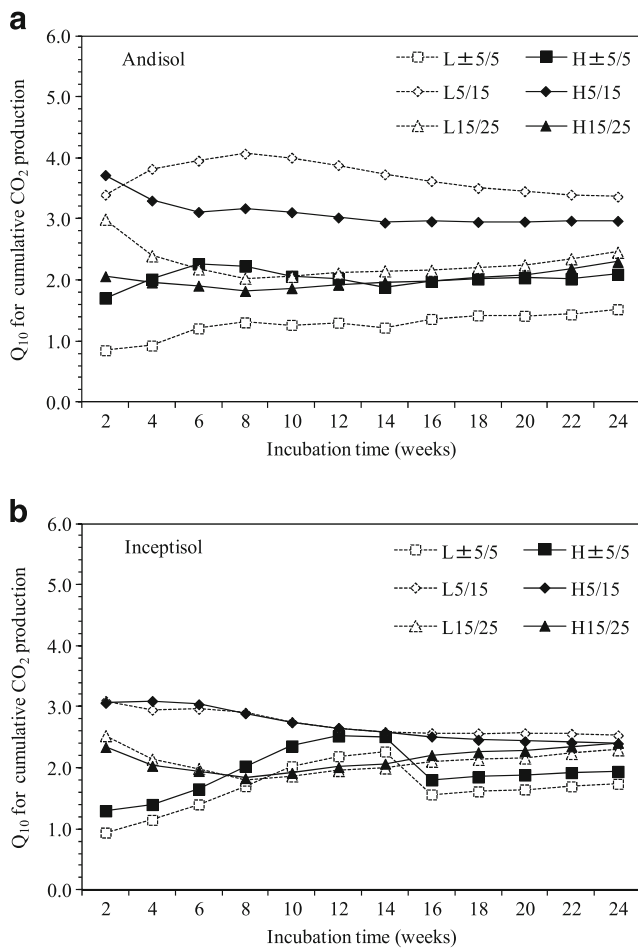
Fig. 2 Values of Q_{10} for SOC decomposition as cumulative CO_2 production in Andisol (**a**) and Inceptisol (**b**) soil samples during the 24-week aerobic incubation under four temperature levels (±5, 5, 15, and 25°C) for both low and high moisture conditions (60 and 100% WFPS). Low (60% WFPS) and high (100% WFPS) moistures are abbreviated to L and H, respectively

samples at previous low temperatures (±5 and 5°C) were distinctly larger than those at high temperatures (15 and 25°C). This suggests that labile organic carbon is more beneficial to CH_4 production during the following anaerobic incubation.

The low CH_4 production during the 4-week anaerobic incubation in both soils can be explained in two reasons. Firstly, it is due to the fact that large part of labile substrate was decomposed during the previous aerobic incubation. Secondly, various electron acceptors in the soil samples were not completely reduced during the 4-week anaerobic incubation (Cheng et al. 2007). It has been previously reported that CH_4 was produced from the decomposition of SOC only after various electron acceptors (e.g., O_2, NO_3^-, Fe(III), and SO_4^{2-}) were completely reduced (Watanabe 1984; Peters and Conrad 1996; Yao et al. 1999; Cheng et al. 2007; Tokida et al. 2010). Substantial accumulation of nitrate was found at the end of aerobic incubation, which would also inhibit CH_4 production in subsequently anaerobic incubation. A significant negative correlation ($P < 0.01$) between CH_4 production under anaerobic condition and nitrate concentration after aerobic incubation was found in two soils in our study (data not shown). Denitrification that occurred during the following anaerobic incubation undoubtedly resulted in nitrous oxide (N_2O) production which has much greater global warming potential than CH_4. In addition, we found a negative effect of the previous soil temperature treatments on the combined CO_2 and CH_4 productions during subsequent anaerobic incubation (Table 1), and significant effects of previous soil temperature and moisture on ratios of anaerobic decomposed C to total decomposed C during both aerobic and anaerobic incubations (Table 3). This revealed that early stage of aerobic SOC decomposition would affect the following anaerobic decomposition of SOC. Based on this finding in our incubation experiment, it implies that to some extent that increasing temperature and moisture in rice paddy field during off-rice season would decrease CH_4 emission during rice growth season.

4.3 Comparison of SOC decomposition between the Andisol and the Inceptisol

The Andisol had higher aerobic CO_2 production than Inceptisol during the 24-week aerobic incubation (Fig. 1). This can be attributed to differences in SOC contents between the Andisol (89.0 g C kg^{-1}) and the Inceptisol (13.6 g C kg^{-1}). However, the aerobic CO_2 production from the Andisol was not greatly larger than those of Inceptisol, despite the 6.5 times SOC differences between the two soils (Table 1). Further, the ratios of anaerobic decomposed C to SOC, and the ratios of

Table 4 The mean values of Q_{10} for SOC decomposition as cumulative CO_2 production obtained from 24-week aerobic incubation of Andisol and Inceptisol soil samples under the four temperature (±5, 5, 15, and 25°C) and two moisture (60 and 100% WFPS) conditions

	Between ±5 and 5°C[a]		Between 5 and 15°C		Between 15 and 25°C	
	Low M.	High M.	Low M.	High M.	Low M.	High M.
Andisol	1.5	2.1	3.4	3.0	2.5	2.3
Inceptisol	1.7	1.9	2.5	2.4	2.3	2.4

Low (60% WFPS) and high (100% WFPS) moistures are abbreviated to Low M. and High M., respectively

[a] ±5°C equal to 0, the difference between ±5 and 5°C was 5

total decomposed C to SOC were largely different between Andisol and Inceptisol (Table 3). These results indicated that a greater fraction of SOC in the Andisol was more stabilized than in the Inceptisol. Our observations are consistent with previous studies. For example, Parfitt et al. (1996) reported that SOC was more stable in the Andisol than in the Inceptisol under two contrasting land uses namely pasture and cropland. It has been reported that Andisol contains abundant noncrystalline and poorly crystalline minerals and oxides which are chemically and physically associated with SOM to form soil organo-mineral complexes (Shoji et al. 1994; Matus et al. 2006; Chevallier et al. 2010). Tate et al. (1990) reported that soil organic matter content in well-developed Andisols could reach up to 20%, and the degree of humification of humic acids in Andisol was higher than that of non-Andisols (Inceptisols, Histosols and Oxisols). This can also be used to explain why the ratio of total decomposed C to SOC was lower in the Andisol than in the Inceptisol in our study.

5 Conclusions

Significant enhancements of SOC aerobic decomposition by soil temperature and moisture were found in both Andisol and Inceptisol soil samples in this study. The total anaerobically decomposed C decreased significantly with the increase of temperature applied during previous aerobic incubation. The rapid depletion of labile substrates and inhibition due to substantial amount of nitrate after aerobic incubation could be responsible for the extremely low CH_4 production during the subsequent anaerobic incubation. These results imply that acceleration of SOC decomposition during off-rice season by increasing soil temperature and moisture might be favorable to mitigate CH_4 production in rice growth season. Despite its high amount of SOC, the fractions of labile C in the Andisol were lower than in the Inceptisol, suggesting that C in the Andisol is more stable than in the Inceptisol. Since this research was conducted on the establishment of incubation experiments, further studies are needed to estimate the effect of temperature and moisture on SOC decomposition in rice paddy fields during both off-rice season and rice growth season.

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