学位論文

Decomposition of rice straw during the off-rice season and methane emission during rice growth season from paddy fields in a cold temperate region in Japan: monitoring and modelling

（日本の寒冷地水田における休耕期稲ワラ分解と
夏季メタン放出量に関する研究）

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ABSTRACT

Methane (CH_4) is the most important greenhouse gas after carbon dioxide (CO_2) and is responsible for approximately 17% of anthropogenic global warming. Rice paddy is a major source of atmospheric CH_4 and is responsible for approximately 11% of the anthropogenic CH_4 release. Paddy soil is known for its high rice productivity and is therefore essential to the sustainability of the rapidly expanding global population. Therefore, reducing CH_4 emissions from submerged rice paddy is imperative to confront both the problem of global warming and food insecurity. In Japanese single crop systems, rice straw as a by-product after grain harvest is commonly left on the field. Rice straw that subsequently becomes incorporated into the soil is partly decomposed aerobically in the fallow season and any remaining parts become substrates for CH_4 production in the next rice growing season. Though a quarter of the total Japanese rice fields are in the northeast (Tohoku) region with cool climatic conditions, there are few studies on the effect of winter temperature and moisture on the aerobic decomposition of rice straw, or on the CH_4 emissions in the next rice growing season. The purpose of this study was to understand how the aerobic decomposition of rice straw during the fallow season of the Tohoku region can affect CH_4 emission during the period following the rice growth season, and to compute the mitigation effect of CH_4 emission from paddy fields in the Tohoku region using model evaluations.

First, an incubation experiment was carried out with Andisol paddy soil, sampled from a field in Morioka, Iwate, Japan. An experiment was designed as a full factorial combination of four temperatures (±5 °C, 5 °C, 15 °C, and 25 °C) and two moisture levels (60% and 100% of water filled pore space), using both bulk soil and soil mixed with 2% of $\delta^{13}C$-labeled rice straw. Straw decomposition rate was calculated using three parameters; CO_2 emission, soil organic carbon (SOC) content, and its $\delta^{13}C$ value. The results indicated that both temperature and moisture affected the rate of rice straw decomposition during the 24-week aerobic incubation period. Rates of rice straw decomposition not only increased with high temperature, but also with high moisture conditions. Rates of rice straw decomposition were more accurately discerned using CO_2 production than those calculated by changes in the SOC content, or in $\delta^{13}C$ value. According to CO_2 measurement, the decomposition rate of rice straw carbon became smaller with a decrease in incubation temperature and was less than 14% even after a 24 week incubation under ±5 °C temperature conditions (12 h intervals of 5 °C and -5 °C), designed to model the freezing- thawing cycles that occur during the fallow season in the Tohoku region.

Second, a field experiment was performed to validate the effect of autumn tillage

(straw incorporation) depth on CH_4 emission from paddy field during the next rice growth season. The experiment took place in an Andisol paddy field in Morioka, Iwate, Japan between 2012 and 2014. CH_4 emissions from the paddy field in the rice growth period, with two levels of tillage depth in autumn (conventional: 15 cm, shallow: 7 cm), were measured periodically. Over the four-year experiment, covering three rice growth seasons, CH_4 emission was not affected by tillage depth in autumn. Although the decomposition rate of rice straw would be affected by both temperature and moisture conditions in general, cumulative CH_4 emission in the early days of the rice growth period was correlated only with cumulative air temperature during the days after straw incorporation in the previous fallow season in this study. Numerical simulations of soil water content revealed that the high permeability of the soil in the experimental field drastically lowered the soil water content soon after the flooding water drained. These results indicate that the CH_4 mitigation mechanism of autumn shallow tillage was limited by soil water conditions in the fallow season, and thus the mitigation effect of shallow autumn tillage would appear only in the field where water content would become high in the fallow season.

Third, a model evaluation for possible CH_4 mitigation effects from shallow autumn tillage in paddy fields was performed with a comprehensive process-based model, DNDC-Rice. The DNDC-Rice model made a correct estimation of cumulative CH_4 emission for six experimental fields around Japan. For evaluating the hypothesis which was obtained from the field experiment carried out in Morioka, virtual conditions of high soil water content in the field during the fallow season was set in the model. However, the DNDC-Rice model showed that cumulative CH_4 emission in the following rice growth season is not affected by autumn tillage depth even with high soil water content in the fallow season. After the current model was revised to increase the degree of inhibition of the organic matter decomposition by excess water, the revised model showed that even though not significant, the trend in CH_4 emission only decreased as a result of autumn shallow tillage with high soil water content conditions.

In conclusion, the results from this study showed that, to decrease CH_4 emissions for the following rice growth season, it is very important to improve aerobic decomposition of rice straw in the early period of the former fallow season with relatively higher temperatures. This is especially relevant in cool regions such as Tohoku region, Japan, where the cool winter climate retards the decomposition rate of organic matter. Further research is needed to reveal the mechanism of CH_4 mitigation options for the application of adequate strategies in different regions with different climates, soil, and farming management conditions.

要旨

メタン(CH_4)は二酸化炭素（CO_2）に次いで放射強制力の大きな温室効果ガスであり、人為的要因による温室効果の約17%がCH_4によるものである。水田は大気中に存在するCH_4の主要な放出源であり、人為的要因により発生したCH4の約 11%が水田由来である。生産性と持続性を兼ね備えた水田稲作はイネ栽培において重要な役割を持ち、水田由来の CH_4 を削減する実用的な対策を模索することは地球温暖化のみならず世界人口の増加に伴う食糧需要の増大に対応するための世界的な課題である。昨今日本の単作稲作において一般的にイネ収穫時の副産物として生成される稲わらは圃場に直接散布される。散布・すき込みされた稲わらは休耕期の酸化分解を経て翌年のイネ生育期における CH_4 生成の基質となる。日本の水田面積のおよそ2.5割が東北地方に分布するが、この東北地方の特徴である冬季の低温が休耕期の酸化分解率および翌年の CH_4 放出量に与える影響について研究した例は少ない。本論文では日本寒冷地の気象条件を考慮し、休耕期における稲わらの酸化分解率と CH_4 放出量との関係を明らかにすること、ならびに水田からの放出 CH_4 量を削減する緩和策を評価することを目的として室内試験、圃場試験、モデル評価を行った。

室内試験では、岩手県盛岡市の黒ボク土壌を用いて、温度・水分量が稲わらの好気分解率に及ぼす影響を調べた。試験には安定同位体^{13}Cでラベルした稲わらを用い、異なる3手法（CO_2発生量、土壌有機炭素含量（SOC）、SOCの$\delta^{13}C$比）で分解率を算出してその水分・温度応答を比較した。試験は水分 2 条件（WFPS60%および100%）、温度4条件（±5℃、5℃、15℃、25℃）の要因実験として実施し、24 週間の培養期間中ヘッドスペースの CO_2 濃度、SOC および SOCの$\delta^{13}C$比について定期的なサンプリングを行った。解析の結果、稲わらの分解率は温度の上昇および水分の上昇によって増加したことが示された。分解率を算出する 3 手法のうち、CO_2 発生量を用いたものが最も高い精度および水分・温度・培養期間の各条件への応答性を示した。CO_2発生量から算出した稲わらの炭素分解率は温度の低下に伴い低下し、東北地域の冬季気象を模した±5℃（12 時間毎に 5℃、−5℃を繰り返す）条件では 24 週間の培養後でも 14%以下に留まった。

圃場試験では、秋耕起時稲わらをすき込む深さが寒冷地水田からの CH_4 放出量に及ぼす影響を評価するため岩手県盛岡市に位置する黒ボク水田圃場において 2012 年から 2014 年にかけて検証試験を行った。秋の耕起深（通常：15cm、浅耕：7cm）を試験条件として設置し、翌年のイネ生育期間中のCH_4放出量を定期的に測定した。3年間の試験の結果より、本試験において秋の耕起深は翌年のCH_4放出量に影響を及ぼさないことが明らかとなった。一般に稲わら分解率は温

度と水分の双方に影響を受けるが、本試験においては CH_4 放出量（イネ生育期間初期）の年間差は前年の稲わらすき込み直後の積算気温のみと相関があることが示された。数値シミュレーションの結果、本試験圃場は透水性が高く落水後直ちに土壌の水分量が減少することが明らかとなった。このことから、秋耕起深の浅化による CH_4 放出量削減メカニズムは過剰水分による分解阻害の改善であり、この緩和策が CH_4 削減効果を発揮するのは休耕期に水分が過剰となる圃場に限られると考えられた。

モデル評価では、包括的プロセスベースモデル DNDC-Rice を用いて秋耕起深を浅くすることによる CH_4 削減効果の評価を行った。本評価に先立って行った検証計算では、DNDC-Rice モデルは日本の 6 地点における慣行秋耕起深（15cm）圃場からの積算 CH_4 放出量を精度よく推定した。圃場試験で得られた仮説を検証するため、休耕期の土壌水分が高い条件を仮想条件として追加した。モデル評価の結果、休耕期の土壌水分は仮想条件の設定により増加したが、秋の耕起深が CH_4 放出量に及ぼす影響は休耕期の土壌水分が高い条件でも明らかでなかった。過剰水分による有機物分解の阻害程度を増加させる試行的なモデル改変を行うと秋耕起の浅化は土壌水分が高い条件でのみ有意ではないものの CH_4 放出量を減少させる傾向を示した。

本研究の結果、特に冬季の低温が有機物の分解を遅延させる冷涼な地域（東北地方）では、休耕期初期の比較的温度が高い時期に投入有機物の好気分解を推し進めることが肝要であることが示された。気象・土壌・管理方法の異なる地域に適切な緩和策を導入するためには緩和策のメカニズム解明が求められ、今後更なる研究が必要である。

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I:

Introduction and Literature Review

1.1 GENERAL INTRODUCTION

Global warming is a well-known problem and is one of the most important global issues. Reports from the Intergovernmental Panel on Climate Change (IPCC) showed that the Earth's surface temperature has been continuously increasing since the 19th Century, and incidental issues such as ocean warming, polar ice melt, and rising sea levels have been observed globally over the past few decades. As a cause of these changes, methane (CH_4) is a significant greenhouse gas which is responsible for approximately 17% of the anthropogenic global warming effect (Fig. I-1, Ciais *et al.*, 2013). CH_4 is mainly produced biologically in nature by methanogens, a type of an anaerobic bacteria which becomes active under reductive conditions, such as in wetlands, the stomachs of ruminants, or paddy fields.

Rice is one of the three main cereal crops grown, together with wheat and maize. Approximately 90% of the world's rice is produced in Asian countries and most of this is planted in the submerged paddy system. Submerged rice paddy is a well-organized rice growing system which has high productivity and sustainability, and accounts for a large fraction of the artificial wetland ecosystem. From the 1980s, scientists have been proving that rice paddy is one of the main sources of CH_4 emissions (Cicerone and Shetter, 1981). According to an assessment report from the IPCC (2013), the CH_4 emitted from rice paddies accounted for 33 to 40 Tg yr^{-1}, equivalent to 10.9% of the global anthropogenic CH_4 release (Fig. I-2). The demand

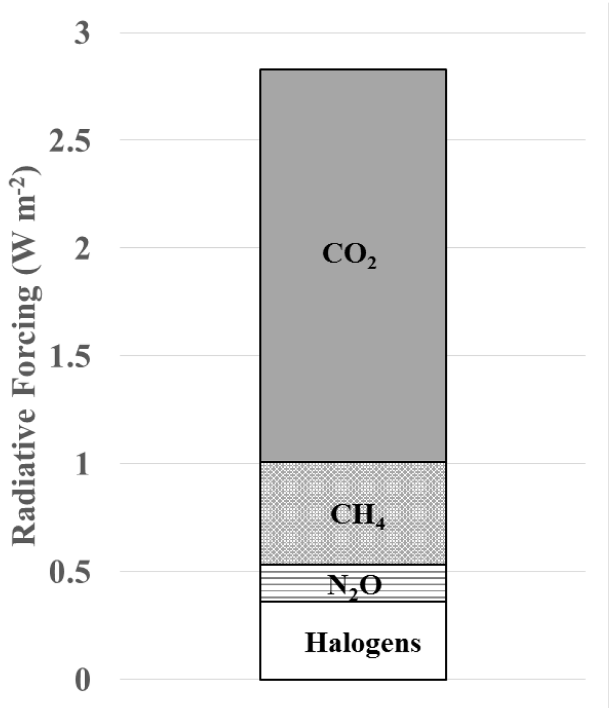

Fig. I-1. Radiative forcing of each Green House Gas

(Data from IPCC (2013))

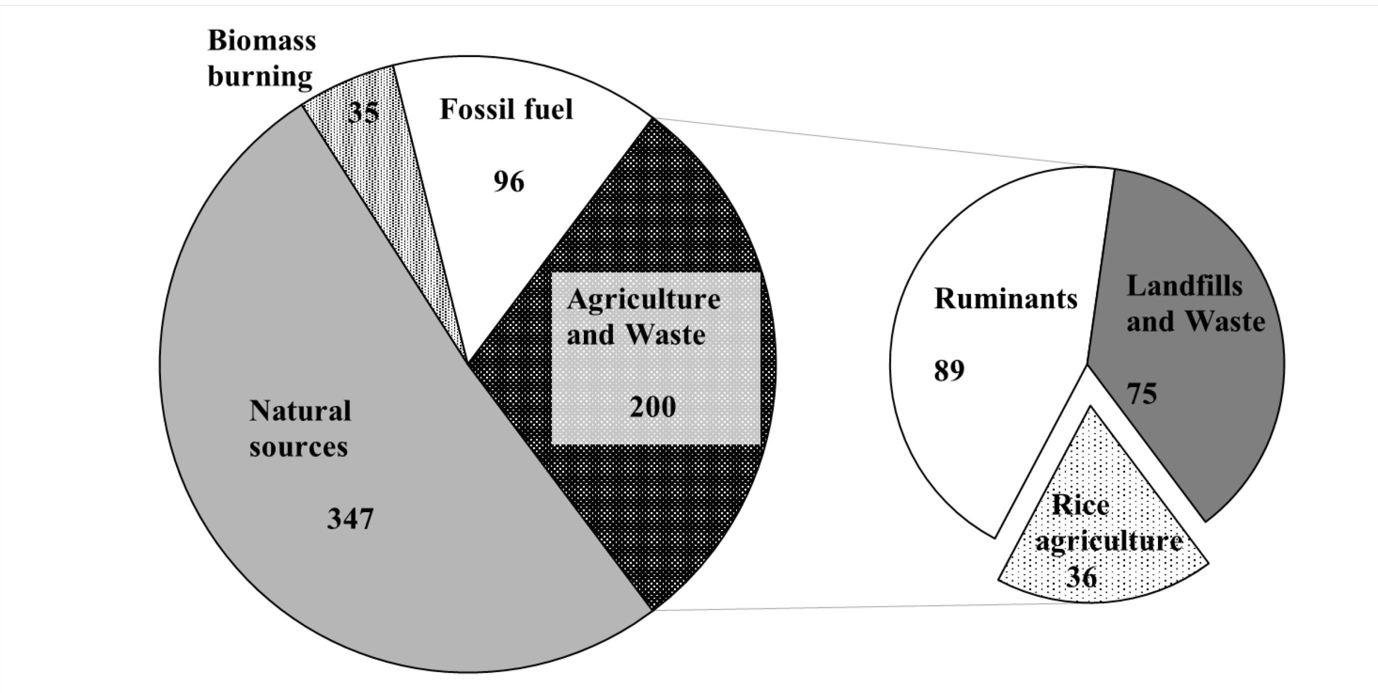

Fig. I-2. Sources of atmospheric CH_4 (Tg (CH_4) yr^{-1})

(Data from IPCC (2013))

for highly productive cultivation systems will probably be further increased in line with the increasing world population. The United Nations (2015) reported that the population of the world increased from 4.8 to 7.3 billion over the past 30-years (1985-2015) and will reach 10 billion in 2060. To confront both the problem of global warming and food insecurity caused by the growth of the world population, seeking a practical way to mitigate CH_4 emission from rice paddy systems is a pressing need.

Many researchers have proposed mitigation strategies for CH_4 production by rice paddies. Among the various kinds of mitigation options, management of the organic matter applied to the fields is a promising means of mitigation, which is applicable even in the rain-fed paddy fields where irrigation systems are not used (Yagi *et al*., 1997). Employing composting processes for organic matter before application has a significant effect on the decrease in CH_4 emissions from paddy fields during the next rice growing season (Yagi and Minami, 1990; Wassmann *et al*., 2000b). However, the intensive use of chemical fertilizers has caused a decrease in the use of rice residues as composted organic fertilizer in the last decades. Residues are scattered on the soil surface by combine harvesters during the harvest of grain, and in the single-cropping system common in the Tohoku region in the northern part in Japan, are often left to decompose aerobically during the winter fallow season. The mitigation option involving the application of composted organic matter currently requires high costs and labor. However, the promotion of the aerobic degradation of rice straw during the fallow season in the field can also decrease CH_4 emissions in the next rice growth season as a more applicable option (Inubushi *et al*., 1994; Yagi *et al*., 1997, Xu and Hosen 2010). Examining and verifying a way to improve the aerobic degradation of rice straw during the off-rice season is needed to find adoptable mitigation options for rice paddy growing systems.

One of the most serious problems in adopting a mitigation strategy to local rice farming is the variety in conditions between each country, region, and field. Straw decomposition rates have large and obvious differences by site and are affected by cumulative temperature (Shiga *et al*., 1985). Especially relevant in high latitude temperate regions, meteorological factors such as temperature, rainfall, and snow strongly affect rice straw decomposition during the off-rice fallow season (Shiono *et al*. 2014). Tohoku is a relatively cold region in Japan where annual mean temperature is approximately 10.5 °C. This region consists of six prefectures and is located at latitudes of 41 °N to 36 °N. Tohoku holds 25% of Japanese paddies and yields 28% of the domestic production of rice in Japan (MAFF, 2015). Hayano *et al*. (2013) simulated national-scale CH_4 emissions in Japan and showed that 54% of the total CH_4 emission from rice paddies was emitted from the Tohoku region. The lower temperature in the winter fallow season in this area restricts the degree of aerobic decomposition of rice straw and thus enhances CH_4 emission in the next rice growing season However, there are few studies that declare how the climatic conditions during the winter in this region affects CH_4 emissions in the field.

The objective of this thesis is to verify the mitigation effects of organic matter management during a fallow season on CH_4 emissions from a paddy field in the next summer, taking into considerations the field conditions in the Tohoku region.

In this study, changes in straw decomposition rate under different temperature and moisture conditions are examined in an incubation experiment considering the field conditions of the fallow season in the Tohoku region (Chapter II). The effects of shallow tillage in autumn as an option to promote the aerobic decomposition of incorporated rice straw on CH_4 emission from paddy fields in the Tohoku region were evaluated (Chapter III). Finally, the effects of shallow tillage in autumn as related to field conditions were simulated with a process-based biogeochemistry model for an extensive evaluation of the CH_4 mitigation effect (Chapter IV).

1.2 LITERATURE REVIEWS

1.2.1 CH_4 emitted from rice paddy fields

There are many previous studies relating to CH_4 emission from paddy fields in the world. A number that are especially concerned with the mechanism of production and consumption of CH_4 in paddy soil, the characterization of CH_4 transmission from the rhizosphere to the atmosphere, the function and limitation of methane-producing bacteria, and the carbon sources for CH_4 production were reviewed. A schematic view of these processes is shown in Figure I-3.

1.2.1.1 Production, oxidation, and emission of CH_4

Methane produced in rice paddy fields is the product of methanogen bacteria, as is most of the atmospheric methane gas. Methanogen are a type of strictly anaerobic bacteria that need severely reductive conditions to thrive. Once a rice field is submerged, the supply of oxygen from the atmosphere to the soil is limited by the surface water. Consumption of the limited oxygen during various reactions in a submerged soil may increase the reductive conditions of the soil over time. Soil reduction proceeds sequentially with the various reduction reactions which have different Gibbs energies. As shown in Figure I-4, O_2 reduction occurs first, followed by NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-} reductions (Ponnamperuma, 1972; Patrick and Jugsujinda, 1992). CH_4 fermentation by methanogens can only occur in an environment where all the electron acceptors except those of CO_2 have been

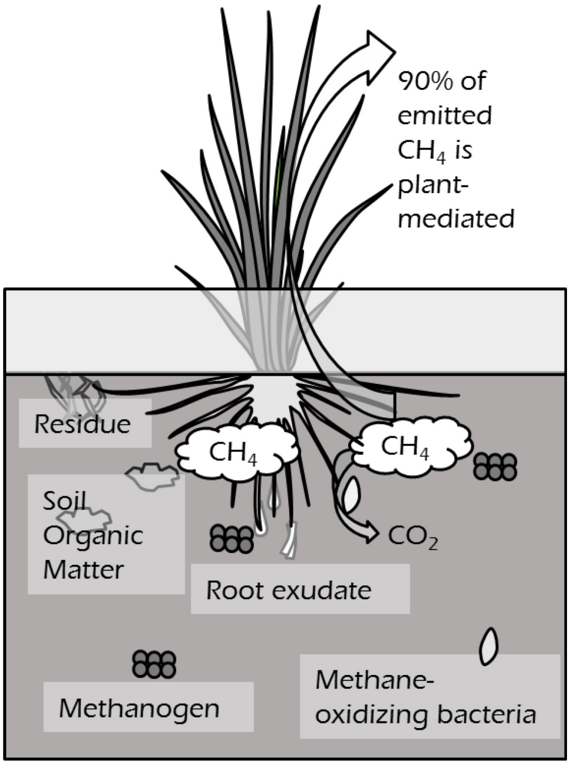

Fig. I-3. Schematic view of CH_4 emission from paddy field

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

$$NO_3^- + 2H^+ + e^- \rightarrow NO_2 + H_2O$$

$$Mn^{4+} + 2e^- \rightarrow Mn^{2+}$$

$$Fe^{3+} + e^- \rightarrow Fe^{2+}$$

$$S + 2H^+ + 2e^- \rightarrow H_2S$$

$$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$$

Fig. I-4. Sequential reductive reactions in submerged soil depleted. Redox potential (Eh) is often used as an index of the degree of reduction in soil. The Eh value at the start of methanogenesis is reported as between -150 and -160 mV. Methanogenesis becomes exponentially more active with decreasing soil Eh (Wang et al., 1993).

Some of the CH_4 produced can be oxidized before its emission to the atmosphere. Oxidation of the produced CH_4 is mainly via methanotrophy, which occurs in the oxic surface layer of paddy soil, in the rhizosphere of rice plants where oxygen is transferred from the atmosphere through the aerenchyma, and inside rice roots (Holzapfel-Pschorn et al., 1985; Frenzel et al., 1992). Oxidation rates vary from between 0-97% of the produced CH_4 and are influenced by various conditions such as the composition of the atmosphere, plant density, or the rice cultivar (Holzapfel-Pschorn et al, 1986; Schütz et al, 1989b; Bilek et al, 1999; Le Mer and Roger, 2001).

The emission of CH_4 from rice paddy is roughly the difference between the production and oxidation of CH_4 in submerged soil (Kogel-Knabner et al., 2010). Other losses of CH_4 such as the loss due to water infiltration account for less than 0.1% of aboveground emission (Minamikawa et al., 2010). Because of its limited solubility in water, the emission rate of CH_4 from a water surface via molecular diffusion is very low. If there is abundant growth of rice plants in a field, more than 90% of the total emission is transported to the atmosphere through the rice plant aerenchyma which acts as pipes between soil and atmosphere (Whiting and

Chanton, 1992). In the very early periods of rice growth, ebullition, bubble formation, and the vertical movement of methane accounts for a certain percentage of total emission because of the low development of the plant aerenchyma.

1.2.1.2 Emission route of CH_4 produced in paddy soil

As mentioned above, the main route of CH_4 emission from paddy fields during the rice growing season is via the aerenchyma of the rice plant. In 1981, Cicerone and Shetter measured CH_4 flux from rice paddies, fresh water lakes and saltwater marshes, and was the first to propose the importance of plant bodies as a transport route for CH_4 emission from wetlands. In 1990, Nouchi *et al*. suggested the idea of CH_4 transport from rhizosphere to atmosphere via rice plants. As these studies revealed, CH_4 is produced in the soil, dissolved in water in the soil, and transported to the inner root cells of the rice plants via diffusion. After that, CH_4 converts to a gas phase in the root cortex, is transported through the aerenchyma, and is ultimately released through micropores in the leaf sheath, not through stomata. While rice plants act as a pipe between rhizosphere and atmosphere, there are individual differences among shoot-root associations. The development of aerenchyma or the activity of associated roots largely influences the rate of CH_4 emission through each rice shoot (Watanabe *et al*., 1994).

1.2.1.3 Substrates of methanogens

Methanogen is a type of *Archaea* and can use limited types of simple compounds as substrate, such as $H_2 + CO_2$, acetate, formate, methylated compounds and primary or secondary alcohols, to gain energy through fermentation (Le Mer and Roger, 2001). These bacteria play an important role in completing the anaerobic mineralization of organic matter. The substrates used by methanogens are provided as a result of the successive degradation of organic matter by several other types of micro-organisms. Most of the methanogenesis in paddy fields occurs by the transmethylation of acetate or the reduction of CO_2 utilizing H_2 (Takai, 1970) as follows:

$$CH_3COO^- \rightarrow CH_4 + HCO_3^- \quad (1)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (2)$$

Through these reactions, methanogens sustain lower concentrations of H_2 or acetate in the soil which inhibits the overall anaerobic decomposition. The reaction in equation (2), of CO_2 reduction with H_2, contributes to about 30-50% (Schutz *et al.*, 1989) or 25-30% (Conrad and Klose, 1999) of the total produced CH_4 in the paddy field.

1.2.1.4 Sources of carbon in paddy fields

Through many previous studies, it is widely known that the application of rice straw or green manure into a field enhances CH_4 emission (Schütz *et al*., 1989a; Yagi and Minami, 1990; Watanabe *et al*., 1993; Tang *et al*., 2014). There are also numerous studies about the effects of plant-borne carbon on CH_4 emissions from paddy fields, such as root exudates or decaying tissue (Chidthaisong and Watanabe, 1997; Aulakh *et al*., 2001; Tokida *et al*., 2011). Concerning sources of carbon which turn to CH_4 under successive degradation, Watanabe *et al*. (1999) mentioned three types of organic matter in paddy fields: applied organic matter such as straw or green manure, soil organic matter (SOM), and carbon released from rice plants (RP) as root exudates, from dead root cells, or as CO_2. The contribution rate of each carbon source to CH_4 emission was measured with the isotopic method, revealing the changes in the contribution rate from each carbon source within each stage of plant growth. In the early stages of rice plant growth, 80% of the emitted CH_4 is derived from applied rice straw (RS). With successive plant growth, CH_4 as derived from RP increases. Finally, the RP replaces the RS as the main source of carbon for CH_4 production in the milk stage. The rate of CH_4 derived from SOM does not change with growth, it remains steady at about 20 % of the total CH_4 emission.

1.2.2 Mitigation options for CH_4 emission

In 1997, Yagi *et al*. categorized the mitigation options for CH_4 emission into four types: water management, soil amendments and mineral fertilizers, organic matter management, and others including tillage, rotation, and rice variety selection. Major previous research concerning CH_4 mitigation strategies are introduced as proposed by the above categories as follows.

1.2.2.1 Water management

One of the most promising strategies for mitigating CH_4 production from rice paddy is water management during the rice growing season (Yagi *et al*., 1997). The adoption of midseason drainage, especially by prolonging this phase or an early start, drastically decreases CH_4 emission from paddy fields in various countries and regions without the loss of yield (Yagi and Minami, 1990; Sass *et al*., 1992; Wassmannn *et al*., 2000b; Itoh *et al*., 2011). This mitigation effect is simply because of environmental changes to the redox potential that is necessary for methanogen activity. Once a field is sufficiently drained, the emission of CH_4 from the field should be less even after re-flooding because of the presence of other electron acceptors such as Fe^{3+} or Mn^{4+}, which also oxidize during drainage (Ratering and Conrad, 1998). While these options have obvious effects on the reduction of CH_4 emission, there are limitations because well-controlled irrigation and drainage systems on a field are required for the adoption of water management.

1.2.2.2 Application of amendments to soil

There is another way to restrain the activity of methanogens using soil environmental control. With the application of other electron acceptors which react with higher Gibbs energy, such as sulfate, ferric iron, or nitrate, methanogenesis will be inhibited or greatly retarded in soil reduction sequences. Substantial previous research concerning this mitigation strategy using sulfate compounds (Schütz *et al*, 1989a; Hori *et al*., 1990; Denier van der Gon and Neue, 1994; Lindau *et al*., 1993; Wassmann *et al*., 2000b; Minamikawa *et al*., 2005), ferric iron (Yoshiba *et al*., 1996; Inubushi *et al*., 1997) or nitrate (Kitada *et al*, 1993; Kluber and Conrad, 1998) has been performed. However, this option is not adoptable everywhere because of several problems; an increase to material costs, the environmental impact on water or the atmosphere, or the risk of decreasing crop yields with surplus applications of such chemicals.

1.2.2.3 Organic matter management

Fresh organic matter such as stubbles or residues of previous crops are often naturally applied on most cultivated fields. Moreover, farmers incorporate additional organic materials for the purposes of increasing soil fertility. Applied organic materials will be decomposed by microorganisms and act as electron donors during sequential reduction processes as mentioned above and thus enhance CH_4 emission. Yagi and Minami (1990) reported that the increase of readily mineralizable carbon (RMC) due to organic matter incorporation can directly affect increases in CH_4 emission. They also declared that composting organic matter before application is significantly effective for the reduction of CH_4 emission. Compost usage instead of fresh rice straw also had obvious mitigation effects in the study of Wassmann *et al*. (2000b). Mitigation options were assessed for eight measurement sites separately for different baseline practices of irrigated, rain-fed, and deep-water rice fields in five Asian countries. For all studies using organic matter application, the usage of rice straw compost reduced CH_4 emission by 58-63% compared to fresh straw incorporation.

Since the mechanism of this mitigation option relies on the reduction of substrate sources usable by methanogens, accelerating aerobic decomposition prior to methanogen activity also has a certain effect. Watanabe *et al*., (1993) reported a decrease in CH_4 emission from the next rice cultivation if the rice straw scattered on the soil surface is only weathered as compared to the application of fresh plant. There are many previous studies concerning the reduction of CH_4 emissions through the promotion of aerobic decomposition of applied organic matter. Incorporation in the soil encourages straw decomposition as compared to that left on the surface (Sain and Broadbent, 1977). The earlier incorporation of rice straw in the fallow season decreases CH_4 emissions in next rice growing season (Inubushi *et al*., 1994; Zhang *et al*, 2013). The addition of urea or ammonium sulfate together with straw incorporation showed clear effects on CH_4 mitigation for the next rice cultivation (Goto *et al*., 2004; Minamikawa *et al*., 2005; Zhang *et al*., 2013). Field conditions in the fallow season also affect the decomposition rate of incorporated rice straw. Natural or artificial drainage promote straw decomposition and thus reduce CH_4 emissions in the next season (Cai *et al*., 2003; Shiratori *et al*., 2007; Xu and Hosen, 2010; Sander *et al*., 2014).

Chapter II:

Modeling aerobic decomposition of rice straw during off-rice season in an Andisol paddy soil in a cold temperate region of Japan: Test the effects of soil temperature and moisture by a laboratory incubation experiment

2.1 ABSTRACT

Submerged rice paddies are a major source of methane (CH_4) which is the second most important greenhouse gas after carbon dioxide (CO_2). Accelerating rice straw decomposition during the off-rice season could help to reduce CH_4 emission from rice paddies during the single rice-growth season in cold temperate regions. For understanding how both temperature and moisture can affect the rate of rice straw decomposition during the off-rice season in the cold temperate region of Tohoku district, Japan, a modeling incubation experiment was carried out in the laboratory. Bulk soil and soil mixed with 2% of $\delta^{13}C$-labeled rice straw with a full factorial combination of four temperature levels (-5 to 5, 5, 15, 25 °C) and two moisture levels (60% and 100% WFPS) were incubated for 24 weeks. The daily change from -5 to 5 °C was used to model the freezing-thawing cycles occurring during the winter season. The rates of rice straw decomposition were calculated by (i) CO_2 production; (ii) change in the soil organic carbon (SOC) content, and (iii) change in the $\delta^{13}C$ value of SOC. The results indicated that both temperature and moisture affected the rate of rice straw decomposition during the 24-week aerobic incubation period. Rates of rice straw decomposition increased not only with high temperature, but also with high moisture conditions. The rates of rice straw decomposition were more accurately calculated by CO_2 production compared to those calculated by the change in the SOC content, or in its $\delta^{13}C$ value. Under high moisture at 100% WFPS condition, the rates of rice straw decomposition were 14.0,

22.2, 33.5, and 46.2% at -5 to 5, 5, 15, and 25 °C temperature treatments, respectively. While under low moisture at 60% WFPS condition, these rates were 12.7, 18.3, 31.2, and 38.4%, respectively. The Q_{10} of rice straw decomposition was higher between -5 to 5 and 5°C than that between 5 and 15°C and that between 15 and 25°C. Daily freezing-thawing cycles (from -5 to 5°C) did not stimulate rice straw decomposition compared with low temperature at 5°C. This study implies that to reduce CH_4 emission from rice paddies during the single rice-growth season in the cold temperate regions, enhancing rice straw decomposition during the high temperature period is very important.

2.2 INTRODUCTION

The decomposition and formation of soil organic matter along with the carbon (C) dynamics in submerged rice paddies is different from that for aerobic soil for wheat and maize, because submerged rice paddies are maintained at lower redox potentials (Takai 1970; Patrick and DeLaune 1972; Inubushi *et al*. 1984). In submerged rice paddies, organic C decomposition not only produce carbon dioxide (CO_2), but also ferment methane (CH_4), which is the most important greenhouse gas after CO_2, and responsible for approximately 17% of the anthropogenic global warming effect (Ciais *et al*., 2013). To decline CH_4 emission from paddy fields, proper management of incorporated residue such as rice straw is effective way to adopt. Especially, promoting aerobic degradation of rice straw in the field during the fallow season can decrease CH_4 emission during next rice growth season (Inubushi *et al*. 1994; Yagi *et al*. 1997, Xu and Hosen 2010). However, straw decomposition rate has large and obvious difference and affected by the cumulative temperature (Shiga *et al.* 1985). Especially in high latitude temperate regions, meteorological factors such as temperature, rainfall and snow strongly affect rice straw decomposition during the off-rice fallow season (Shiono *et al*. 2014). As shown in Figure II-1 for Morioka, Iwate, Japan, the ten-days mean of air temperature in past 30 years during fallow season change from 14.4 °C to -2.2 °C. And the difference of maximum and minimum air temperatures from October to May is about 26.0 °C (Figure II-1a). Additionally, soil moisture might be changed

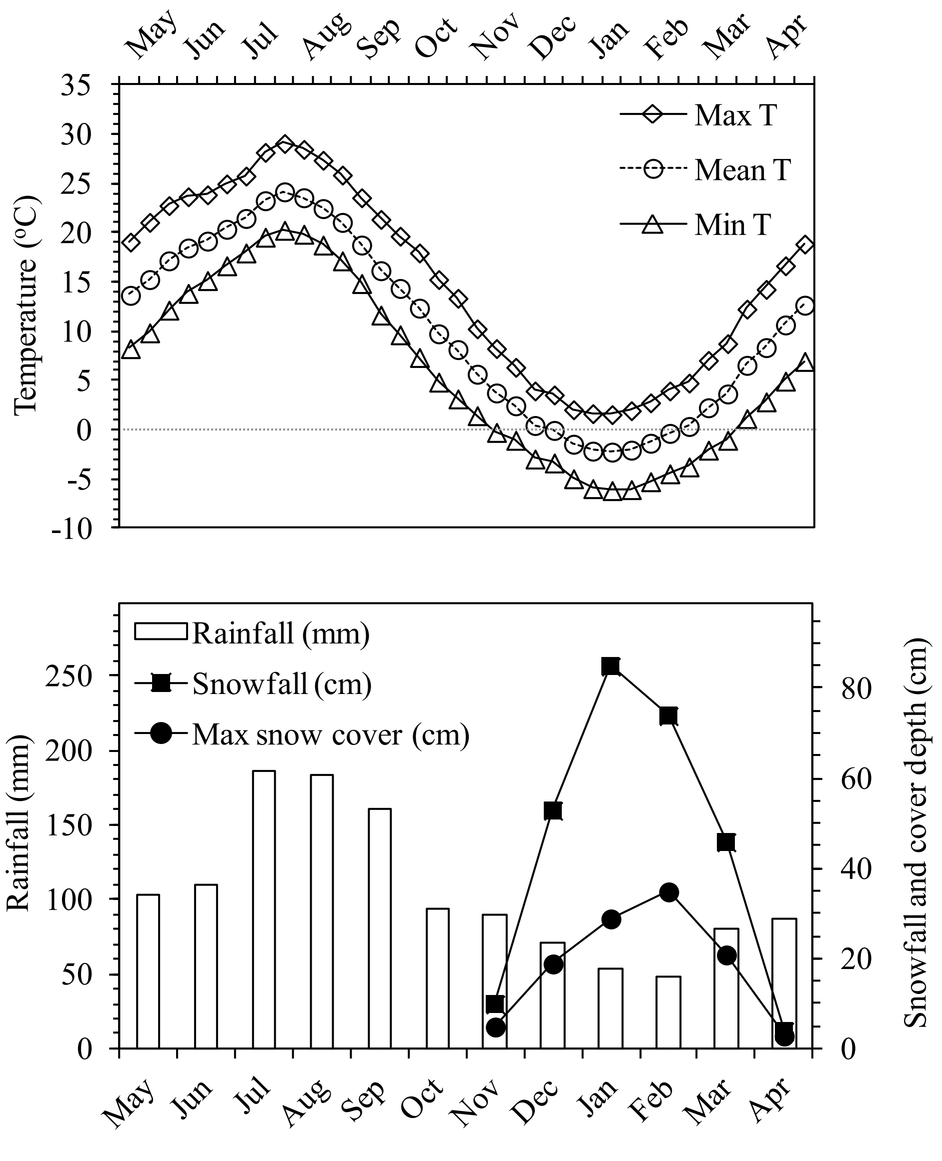

Fig. II-1. The averages of maximum, mean and minimum air temperatures (T) for each ten days from May to April (a); the monthly rainfall, snowfall and maximum snow cover in the winter season (b) in Morioka, Iwate, Japan. Data are the average values for the period 1981-2010 and provided by Japan Meteorological Agency.

by the presence of a long snow-covered period during off-rice season (Figure II-1b). However, it is not clear how rice straw decomposition can be affected by temperature and soil moisture in rice-off fallow season, especially in cold temperate region, Japan.

Organic matter decomposition is an attracting topic through the ages. In 1930s, early studies declared how temperature and moisture affect plant residues decomposition (Waksman and Gerretsen 1931; Acharya 1935). In both of these classic studies, residue decomposition was measured with single plant residue without mixing to soils, and the loss of dry matter or constituents of residue were mainly used to evaluate its decomposition. Measuring the difference of organic contents before and after incubation period is often used as a simple way to evaluate the organic decomposition in both of incubation and field experiments (Shiga *et al*. 1985; Goto *et al*. 2004). In well-controlled incubation tests, amounts of emitted gases (CO_2 and/or CH_4) as results of organic decomposition by microorganisms could also be used as an index of decomposition rate (Devêvre and Horwáth 2000; Zhou *et al*. 2014). This approach has the advantage to allow the monitoring of the decomposition dynamics within brief intervals. After stable isotope technology has spread, ^{13}C and ^{15}N-labeled rice straw was used to study rice straw decomposition in soil and its effect on rice growing (Pal and Broadbent 1975; Yoneyama and Yoshida 1976; Watanabe *et al*. 1999). The use of labeled or natural isotope ratio can allow tracking the flow of C in soil during whole of the processes from incorporation as a plant residue to emission as a gas.

The objectives of this experiment were firstly to investigate how rice straw decomposition rate was affected by both temperature and soil moisture in an Andisol paddy soil from a cold temperate region, by modeling various climatic conditions for the off-rice season in Tohoku district, Japan. Secondly, we aimed to evaluate the difference among three methods (CO_2 productions, SOC and $\delta^{13}C$ value changes) used for calculating rice straw decomposition rate during a 24-week incubation experiment.

2.3 MATERIALS AND METHODS

2.3.1 Soil, straw and pre-incubation

Andisol soil was collected from the top layer (0-10cm depth) of a rice field in National Agricultural Research Organization (NARO) Tohoku Agricultural Research Center located in Morioka, Iwate prefecture (39°42′N, 141°09′E), where a field experiment was carried out described in Chapter III. Soil was air-dried and sieved (2 mm), and obvious plant debris in soil was removed with tweezers to minimize the influence of residual straw and root debris before the laboratory incubation experiment. The added rice straw used in this experiment was obtained from a controlled-environmental chambers experiment carried out in the National Institute for Agro-Environment Sciences, in which rice plants received a mixture of ambient and ^{13}C-depleted commercial CO_2. The straw was ground into small pieces (< 2 mm) before use for laboratory incubation. The value of $\delta^{13}C$ in rice straw was -36.69 ‰. The initial properties of the soil and rice straw are shown in Table II-1.

An air-dried bulk soil sample was pre-incubated at 40% water-filled pore space (WFPS) and 25 °C for 4 weeks before the aerobic incubation experiment. The WFPS was calculated as: WFPS = [(gravimetric water content × soil bulk density)/total soil porosity], where total soil porosity is [1 − (soil bulk density/ 2.65)] and 2.65 is the assumed particle density of the soil (Cheng *et al.*, 2004).

Table II-1. Initial properties of the Andisol bulk soil and rice straw (RS)
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	Bulk soil	Rice straw	Soil after added RS*	
pH (H_2O)	5.84		-	-
EC (μS cm^{-1})	101.7		-	-
Total organic C (g C kg $soil^{-1}$)	89.0	399.2	95.1	
Total N (g N kg $soil^{-1}$)	6.70	4.88	6.66	
C: N ratio	13.29	81.76	14.27	
$\delta^{13}C$ of total organic C (‰)	-22.20	-36.69	-23.39	

*RS was added to soil with 2% in the weight of dry soil.

2.3.2 Aerobic incubation experiments

According to the soil temperature and moisture situation in the field during the off-rice fallow season in the cold temperate region at Tohoku district, Japan, four soil temperature levels [-5 to +5 (denoted by ±5), 5, 15, 25 °C] and two soil moisture levels (low WFPS at 60% and high WFPS at 100%; abbreviated L and H, respectively) were designed for this aerobic incubation. Therefore, the two factors of soil temperature and moisture were combined into eight environmental conditions, namely L±5, L05, L15, L25, H±5, H05, H15 and H25, respectively. The ±5 °C incubation condition was designed for the soil temperature change between day (12 h) and night (12 h) with the corresponding freezing and thawing cycles. For measuring rice straw decomposition in Andisol soil under the eight environmental conditions, main treatments of both control bulk soil (control, abbr: C) and 2% of rice straw-added soil (straw added, abbr: S) were used. Each treatment had three replications.

After the bulk soil sample was pre-incubated at 40% WFPS for 4 weeks, 10 g (oven-dried basis) of soil was placed into 100-mL plastic bottles (total 192 bottles), and then 0.2 g of ground rice straw (2% of soil weight) were added to half of the bottles (total 96 bottles) and thoroughly mixed by hand shaking. Finally, pure water was added with a mini-pipette to adjust the control and straw-added soils to 60% and 100% WFPS. All plastic bottles were loosely covered with caps to maintain aerobic conditions, and were then incubated at ±5, 5, 15 and 25 °C. During the incubation, loss of water was corrected every 3 or 4 d using a mini-pipette. Three replicates for each treatment were removed from the incubators after 6, 12, 18 and 24 weeks, respectively, and soil samples were oven-dried at 70 °C and ground for measuring changes in contents and $\delta^{13}C$ values of SOC. The contents and $\delta^{13}C$ values of SOC in the soils were determined by dry combustion (SUMIGRAPH NC-220F, Sumika Chemical Analysis Service, Ltd, Japan) and isotope ratio mass spectrometer (IR-MS; Flash 2000, Delta V Plus; Thermo Scientific, Germany).

In parallel, 5 g (on an oven-dried basis) of soil was placed into 68-mL glass serum bottles (total 48 bottles) to measure CO_2 production from the control and straw-added soils under the four temperature and two soil moisture conditions. The procedure was the same as for the plastic bottles. Before incubation, each bottle was capped with a butyl rubber stopper with aluminum seal and purged with pure air (80% N_2 + 20% O_2). Every 2 weeks throughout the incubation period, the CO_2 production was measured for all incubation samples by collecting the gas from the headspace of each glass serum bottle. The butyl rubber stopper and aluminum seal were replaced with new ones after gas sampling, and the headspace air was purged with pure air again.

CO_2 concentration was measured using gas chromatography (Shimadzu GC-7A, Kyoto, Japan) with a thermal conductivity detector (TCD). The cumulative CO_2 productions from each soil sample during the incubation periods of 6, 12, 18, and 24 weeks were calculated from the bi-weekly production (Cheng *et al*. 2007). CH_4 emission was not detected in this incubation experiment.

2.3.3 Calculating the rate of rice straw decomposition based on CO_2, SOC and $\delta^{13}C$

Rice straw decomposition rates (Dec R) were calculated individually for each of the three parameters using the following equations. The average values of CO_2 production, SOC content and $\delta^{13}C$ for each treatment were used.

(i) Calculation based on CO_2 production

$$\text{DecR (\%)} = \frac{CO_2\_C_{str} - CO_2\_C_{ctr}}{Added\ straw\ C} \times 100 \qquad (1)$$

where $CO_2\_C_{str}$ and $CO_2\_C_{ctr}$ (mg C kg^{-1} soil) are C-CO_2 production from straw-added soils and control soils after incubation, respectively. Added straw C is the amount of C in the rice straw added to the soil; here the amount is 7.83 g C kg^{-1} soil.

(ii) Calculation based on the changes in the SOC content

$$\text{Dec R (\%)} = \frac{Added\ straw\ C - (SOC_{str} - SOC_{ctr})}{Added\ straw\ C} \times 100 \qquad (2)$$

where SOC_{str} and SOC_{ctr} (g C kg^{-1} soil) are the contents of soil organic carbon after incubation in straw- added soils and control soils, respectively. The difference between SOC_{str} and SOC_{ctr} corresponds to residual C derived from rice straw. Added straw C is the amount of C in the rice straw added to the soil; here the amount is 7.83 g C kg^{-1} soil.

(iii) Calculation based on the changes in $\delta^{13}C$ value

The change in the fraction of rice straw C during incubation period (*F*) in the straw-added soil was calculating with eq. (3) (Balesdent *et al*. 1988; Cheng *et al*. 2010):

$$F = \frac{\delta_{str} - \delta_{ctr}}{\delta_{ori-str} - \delta_{ctr}} \qquad (3)$$

where δ_{str} and δ_{ctr} are the $\delta^{13}C$ values (‰) of organic carbon in straw-added soils and control soils, respectively. $\delta_{ori-str}$ is the $\delta^{13}C$ values of original rice straw (-

36.694 ‰, Table II-1).

$$\text{Dec R (\%)} = \frac{F_{ini} - F}{F_{ini}} \times 100 \qquad (4)$$

where F_{ini} is the initial fraction of rice straw C, with a value of 8.23%, referring to Table II-1.

2.3.4 Calculating the Q_{10} of rice straw decomposition and statistical analyses

Since four temperature levels (±5, 5, 15 and 25 °C) were adopted in this incubation experiment, the Q_{10} temperature coefficient was calculated as:

$$Q_{10} = \left(\frac{Dec\ R_2}{Dec\ R_1}\right)^{\frac{10}{T_2 - T_1}} \qquad (5)$$

where Dec R is the rate of rice straw C decomposition and T is the temperature level of ±5, 5, 15, and 25 °C, respectively. Here ±5 °C for a daily temperature change in the -5 and 5°C treatment was averaged as 0 °C.

An analysis of variance (ANOVA) was employed to determine the effects of temperature, moisture, incubation time and their interaction on CO_2 production, SOC content and $\delta^{13}C$ values of the control and straw-added soils. The statistical analysis was performed using IBM SPSS statistics version 21 software.

2.4 RESULTS

2.4.1 CO_2 production affected by different temperature and moisture treatments

The changes in CO_2 productions from the control and straw-added soils during the 24-week incubation period are shown in Fig.II-2 for both (a) low and (b) high moisture. A large flush CO_2 production was observed in the straw-added soils at 15 and 25 °C under two soil moisture conditions during the first 6 weeks (P<0.05). After 6 weeks of incubation, CO_2 production from straw-added soils decreased slowly and remained stable until 24 weeks. Mostly, the CO_2 production from control soils among all temperature and moisture treatments was stable except a small peak was observed during the first 4 weeks at 25 °C. The cumulated CO_2 production at 6, 12, 18 and 24 weeks of incubation under different temperature and moisture conditions is shown in Fig. II-3a, and the cumulative CO_2 production during the 24 weeks is shown in Figure II-4. The ANOVA results show that the cumulated CO_2 production in all treatments was significantly affected by temperature, moisture, time and the interaction of these three factors (P < 0.001; Table II-2).

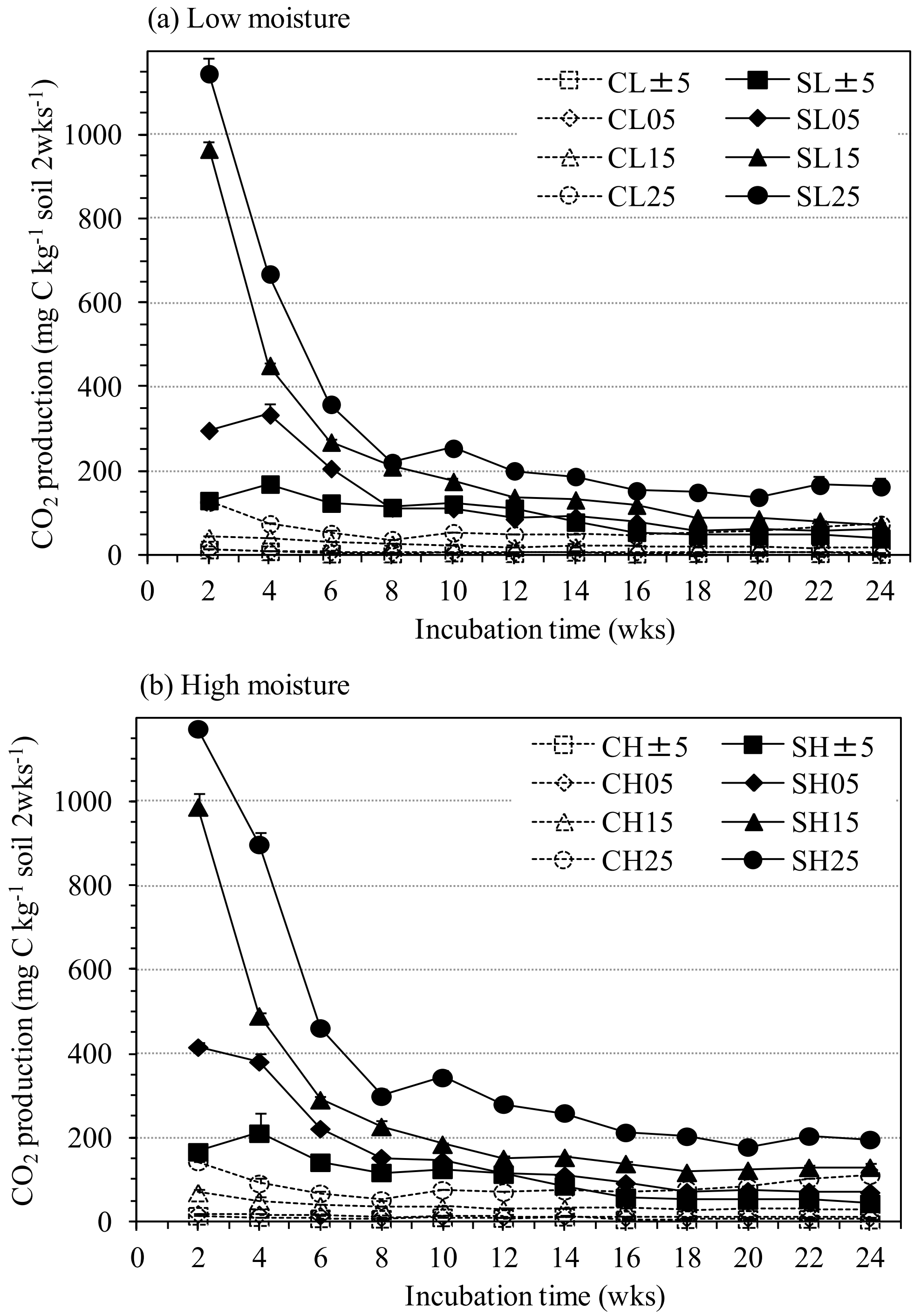


Fig. II-2. Changes in CO_2 production from both control and rice straw-added soils during the 24-week incubation under low (a) and high (b) soil moisture conditions and four temperature treatments. Bars indicate the standard deviation (n = 3). Control and rice straw-added soils were abbreviated to C and S, respectively. Low and high soil moistures were abbreviated to L and H, respectively.

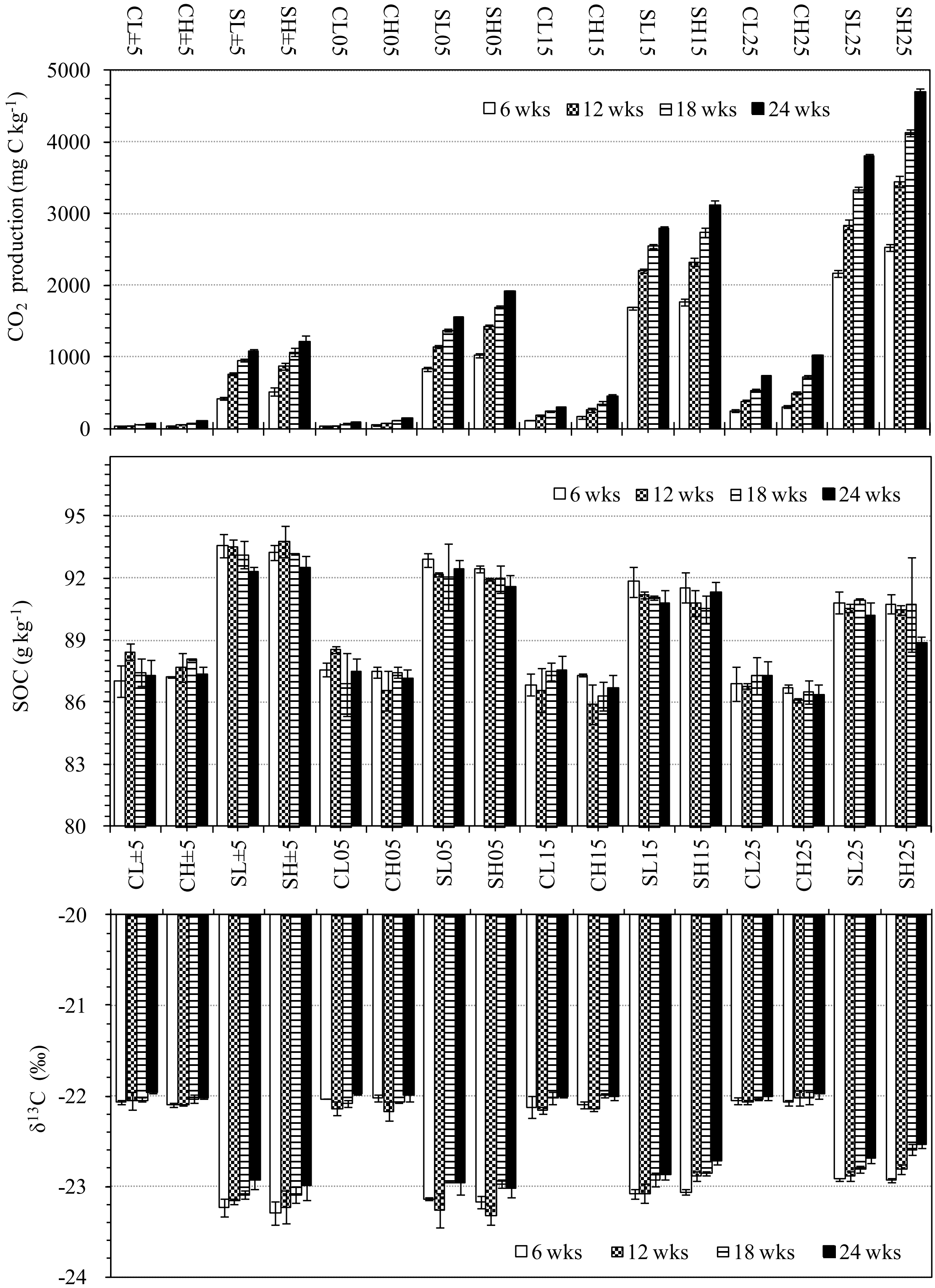
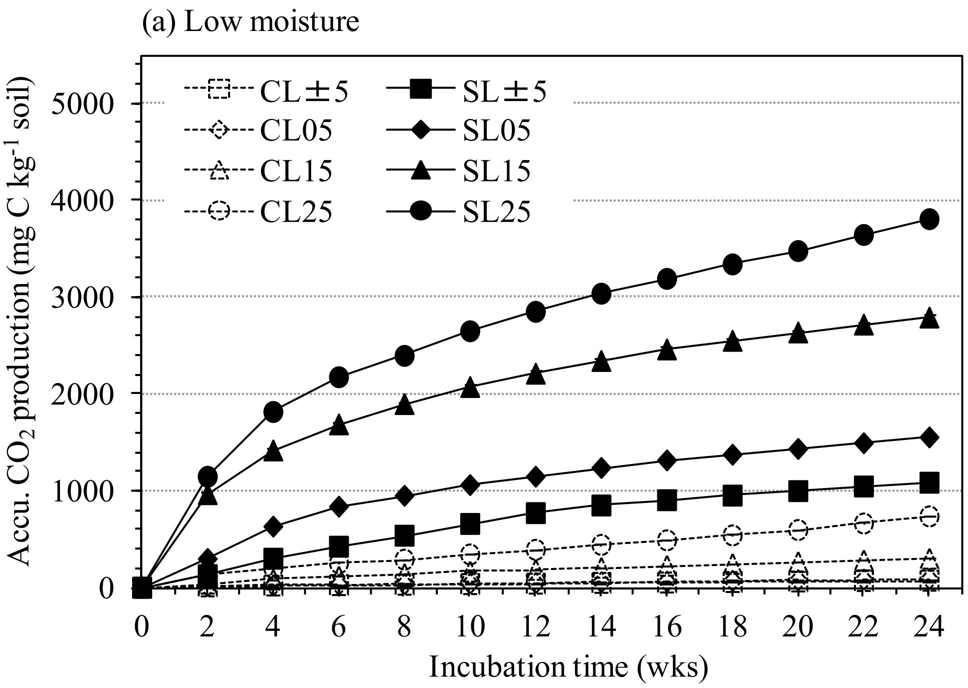


Fig. II-3. Changes in CO_2 production (a), SOC content (b), and $\delta^{13}C$ values (c) of both control and rice straw-added soils after 6, 12, 18, and 24 weeks of the incubation under different soil moisture and temperature conditions. Bars indicate the standard deviation (n = 3). Control and rice straw-added soils were abbreviated to C and S, respectively.



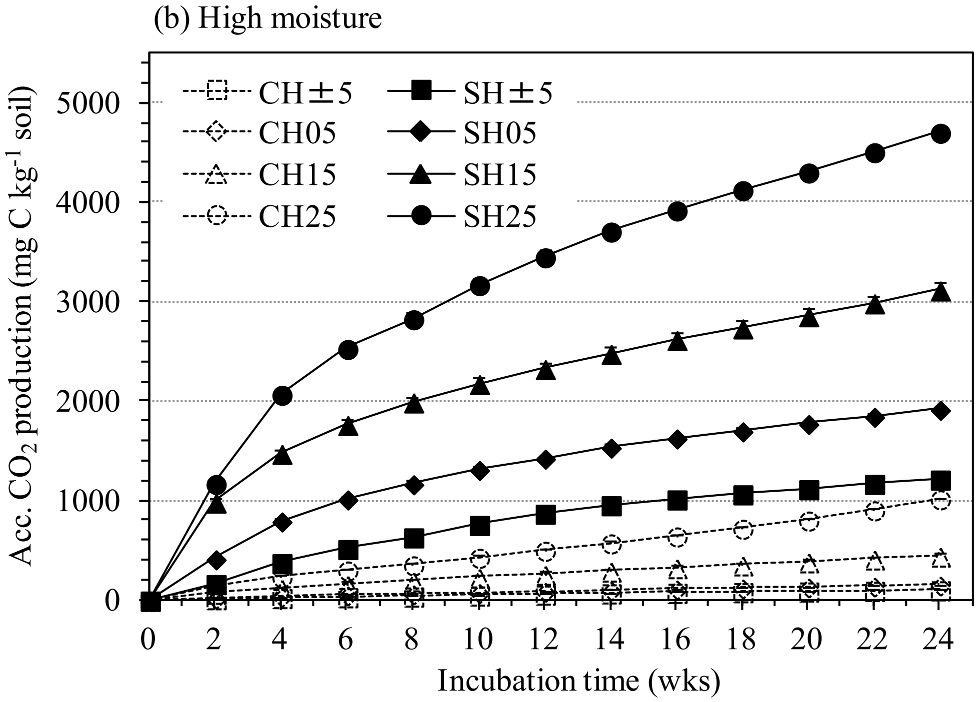


Fig. II- 4. Changes in cumulated CO_2 production from control and rice straw-added soils during the 24-week incubation under the low (a) and high (b) moisture conditions, and four temperature treatments. Bars indicate the standard deviation (n = 3). In most cases, the bar is covered by the symbol. Control and rice straw-added soil were abbreviated to C and S, respectively.

2.4.2 Changes in SOC contents under different temperature and moisture conditions

Changes in SOC contents after 6, 12, 18 and 24 weeks of incubation were shown in Figure II-3b. The average SOC contents of the control soils and straw-added soils under different temperature and moisture conditions decreased during incubation and became lower than those of the original soils（89.0 and 95.1 g C kg^{-1}, respectively; Table II-1). However, these changes were not always deceasing with incubation time (6, 12, 18 and 24 weeks), contrary to logical expectation. The ANOVA results show that SOC contents of the control soils were significantly affected by temperature ($P < 0.001$) and soil moisture ($P = 0.003$), but not by incubation time ($P = 0.949$). For straw-added soils, the changes in SOC were significantly affected by temperature ($P < 0.001$) and incubation time ($P < 0.001$) but not significantly affected by soil moisture ($P = 0.092$) (Table II-2).

2.4.3 Changes in $\delta^{13}C$ value under different temperature and moisture conditions

Changes in $\delta^{13}C$ value after 6, 12, 18 and 24 weeks of incubation are shown in Figure II-3c. The means of $\delta^{13}C$ values for the control soils and straw-added soils under different temperature and moisture conditions were higher compared to the original soil before incubation (-22.20 ‰ and -23.39 ‰, respectively; Table II-1). The ANOVA results show that the $\delta^{13}C$ values were significantly affected by temperature for the straw-added soils ($P < 0.001$), but not for the control soils ($P = 0.064$). The temporal change in $\delta^{13}C$ values in the control soil and straw-added soil throughout the incubation period was significant ($P < 0.001$), but in some cases, the $\delta^{13}C$ values at 6 weeks were higher than those at 12 weeks (Fig. II-3c). For the straw-added soil, the interactive effect between temperature and moisture was also significantly (Table II-2).

Table II-2. The P values from analysis of variance (ANOVA) of main-plot factors of temperature and moisture, split-plot factor of incubation time on cumulative CO2 productions,

Source	CO_2 production		SOC content		value of $\delta^{13}C$	
	Control bulk soil	Straw added soil	Control bulk soil	Straw added soil	Control bulk soil	Straw added soil
	Pr>*F*					
Temperature (Temp)	<0.001	<0.001	<0.001	<0.001	0.064	<0.001
Moisture (Mois)	<0.001	<0.001	0.003	0.092	0.848	0.071
Temp × Mois	<0.001	<0.001	0.252	0.611	0.342	0.001
Time	<0.001	<0.001	0.949	<0.001	<0.001	<0.001
Time × Temp	<0.001	<0.001	0.046	0.115	0.004	0.019
Time × Mois	<0.001	<0.001	0.024	0.944	0.779	0.350
Time × Temp × Mois	<0.001	<0.001	0.169	0.605	0.950	0.634

2.4.4 Comparison of the three calculation approaches of rice straw decomposition rate

Rice straw decomposition rates calculated using the three methods are shown in Figure II-5. Theoretically the rates should be the same, but the results were different among the three methods used in this study.

Rice straw decomposition rates calculated by CO_2 production showed a steady increase with incubation time, temperature and moisture in Figure II-5a. After 24 weeks of incubation, the highest rice straw decomposition rate calculated by CO_2 production was 46.2% under the high moisture (100%WFPS) and 25 °C condition (H25), and the lowest was 12.7% under the low moisture (60% WFPS) and ±5 °C condition (L±5).

Rice straw decomposition rates calculated by SOC contents were the highest at 68.5% under the high moisture and 25 °C condition (H25) after 24 weeks of incubation, and were the lowest at 33.5% under the high moisture and ±5 °C condition (H±5). The decomposition rate values calculated by SOC contents were always higher than those based on CO_2 production (Fig. II-5a, b). Moreover the rates calculated from SOC contents showed little tendency with incubation time, temperature and moisture.

After 24 weeks of incubation, the rice straw decomposition rate calculated by $\delta^{13}C$ values was the highest at 53.6% under the high moisture and 25 °C condition (H25), and was the lowest at 14.5% under the high moisture and 5 °C condition

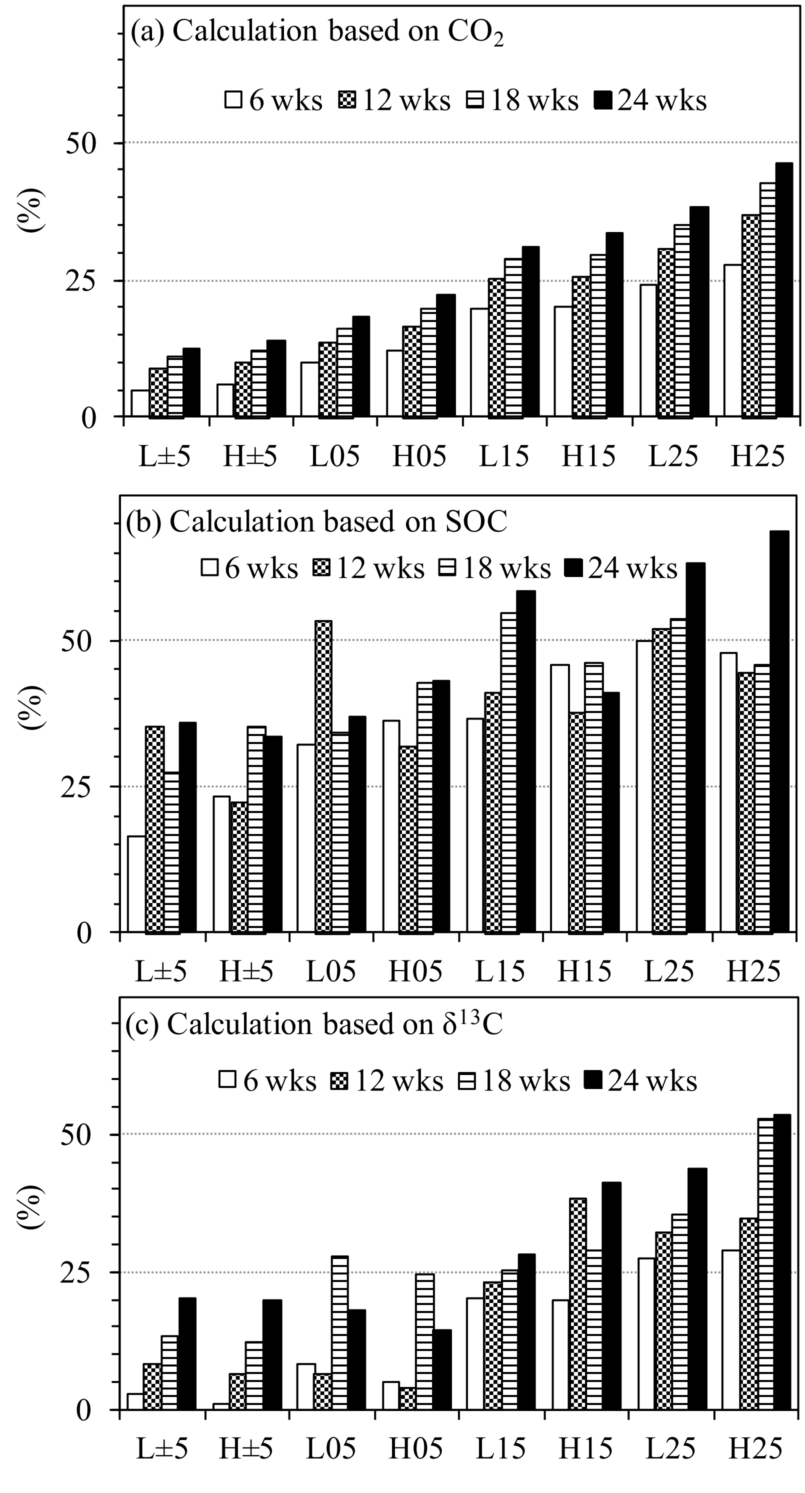


Fig. II-5. Rates of rice straw carbon decomposition after 6, 12, 18, and 24 weeks of incubation. The calculations were based on CO_2 production (a), SOC contents (b), and $\delta^{13}C$ values (c) among the two moisture and the four temperature treatments.

(H05). Mostly, the rice straw decomposition rate increased with incubation time, but under both 5 °C conditions (L05, H05) the rates after 24 weeks were lower than those after 18 weeks.

2.4.5 Changes in the Q_{10} of rice straw decomposition

The mean Q_{10} values of rice straw decomposition rates under the four temperatures and two moisture treatments, calculated from the data after 6, 12, 18 and 24 weeks of incubation, are shown in Table II-3. The Q_{10} values between 5 and ±5 °C were larger than the values between 15 and 5 °C and between 25 and 15 °C, though the values calculated using the three methods were different. Moreover, the Q_{10} values between 15 and 5 °C were larger than the values between 25 and 15 °C in most cases, except for calculations based on SOC contents under high moisture conditions (Table II-3). Among the three methods, the values of Q_{10} of rice straw decomposition rates were higher when based on $\delta^{13}C$ values, and lower when based on SOC contents.

Table II-3. The mean values of Q_{10} of rice straw decomposition rates under 4-level temperatures at both low and high moisture treatments, calculating by the data after 6, 12, 18 and 24 weeks incubation

	by CO_2		by SOC		by $\delta^{13}C$	
	Low M.	High M.	Low M.	High M.	Low M.	High M.
Between 05 and ±5 °C*	2.66	2.95	2.18	1.89	3.46	7.11
Between 15 and 05 °C	1.81	1.56	1.27	1.12	2.13	4.62
Between 25 and 15 °C	1.22	1.41	1.17	1.22	1.44	1.38

*±5°C equal to 0, the difference between 05 and ±5 °C was 5.

2.5 DISCUSSION

In this research, we simulated various climatic conditions (four temperature conditions and two moisture levels) for the off-rice fallow season in the cold temperate region of Tohoku district, Japan, to study the aerobic decomposition of rice straw in an Andisol paddy soil. Unlike previous studies using nylon bags or fiber-filter paper bags (Shiga *et al*. 1985; Goto *et al*. 2004), we mixed ^{13}C-labeled rice straw into the Andisol soil (high SOC content at 89.0 g kg^{-1} soil) and measured three parameters —CO_2 production, SOC content and $\delta^{13}C$ value —periodically during a 24-week incubation experiment from both control and rice straw-added soils based on the difference between SOC and rice straw decompositions.

The CO_2 production derived from microbial heterotrophic respiration was significantly affected by temperature, moisture, incubation time and their interactions for both control and straw-added soils ($P < 0.001$; Table II-2; Figs II-2 and II-3a). Changes in SOC content and in $\delta^{13}C$ value were only slightly influenced by incubation conditions and showed a larger experimental error than the measurements of CO_2 production. In this study, we used an Andisol with high SOC content. A high content of background soil carbon might amplify the uncertainties in the measurements and calculation of the changes in SOC content and $\delta^{13}C$ value throughout the incubation experiment, making the sensitivity lower for these two methods compared to the measurements of CO_2 production. Also, the inhomogeneity of SOC, the equipment accuracy of SUMIGRAPH NC-220F, and isotope fractionation effects of SOC decomposition would be made the sensitivity lower by measurement of SOC content and δ^{13}C value than by measurement of CO_2 production.

Additionally, for SOC content and δ^{13}C value, the effect of moisture was mostly weaker than that of temperature (Table II-2 and Tables II-4-6). The reason for this may be the smaller range of WFPS treatments (60% and 100% WFPS) than of temperature levels (from ±5 °C to 25 °C).

Freezing-thawing processes are known to affect soil and plant residue composition, leading to changes in C and N cycles in the soils (Yanai *et al*. 2004; Wu *et al*. 2015; Xu *et al*. 2015). But in this study, CO_2 production in the ±5 °C treatment was lower than that in the 5 °C treatment under both low and high moisture conditions. Though we did not design a 0 °C treatment for comparison with ±5 °C in this study, the effect of freezing-thawing processes on SOC and straw composition was not clearly remarkable.

The rates of rice straw decomposition resulting from calculations based on the three parameters of CO_2 production, SOC content and δ^{13}C value were obtained from this incubation experiment. The decomposition rate of each method was calculated with the differences between the values for control and for rice straw-added soils, respectively. The CO_2 production corresponds to the heterotrophic respiration, which directly highlight SOC and rice straw C decomposition by soil microorganism activities. The changes in content and δ^{13}C value of SOC during the

Table II-4. The cumulative CO_2 (mg C kg soil^{-1}) emissions and their analysis of variance from the control bulk soil (C) and rice straw added soil (S) under 2 moistures and 4 temperatures regimes after 6, 12, 18 and 24 weeks incubation.

Tempe-rature	Soil moisture in WFPS	Code	6 weeks		12 weeks		18 weeks		24 weeks	
			C	S	C	S	C	S	C	S
±5 °C	60 %	L±5	26.7	423.2	41.8	770.0	58.7	950.6	72.2	1083.9
	100 %	H±5	33.8	518.7	60.6	873.8	84.6	1068.6	103.3	1217.2
5 °C	60 %	L05	29.3	836.4	47.7	1145.8	69.9	1372.8	89.1	1551.6
	100 %	H05	50.9	1017.1	86.2	1427.7	120.2	1702.1	149.5	1918.4
15 °C	60 %	L15	115.8	1686.0	185.2	2209.2	245.2	2548.5	299.8	2788.6
	100 %	H15	158.6	1766.3	260.6	2328.1	354.7	2737.4	443.8	3118.9
25 °C	60 %	L25	252.6	2172.8	391.3	2848.1	539.8	3337.7	736.0	3804.7
	100 %	H25	302.3	2530.7	500.9	3452.2	722.3	4127.0	1018.6	4704.5
Source of variation			ANOVA results (*P>F*)							
Temperature (Temp)			0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Moisture (Mois)			0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Temp x Mois			0.041	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table II-5. The chenges in SOC (g C kg soil^{-1}) and their analysis of variance in the control bulk soil (C) and rice straw added soil (S) under 2 moistures and 4 temperatures regimes after 6, 12, 18 and 24 weeks incubation.

Tempe-rature	Soil moisture in WFPS	Code	6 weeks		12 weeks		18 weeks		24 weeks	
			C	S	C	S	C	S	C	S
±5 °C	60 %	L±5	87.01	93.55	88.44	93.52	87.44	93.14	87.26	92.29
	100 %	H±5	87.23	93.23	87.67	93.77	88.08	93.15	87.33	92.54
5 °C	60 %	L05	87.58	92.90	88.52	92.18	86.87	92.04	87.51	92.44
	100 %	H05	87.46	92.45	86.58	91.93	87.45	91.95	87.16	91.61
15 °C	60 %	L15	86.85	91.82	86.57	91.19	87.50	91.05	87.54	90.79
	100 %	H15	87.32	91.55	85.88	90.78	86.28	90.51	86.68	91.29
25 °C	60 %	L25	86.87	90.80	86.77	90.55	87.27	90.89	87.29	90.18
	100 %	H25	86.67	90.76	86.12	90.46	86.50	90.75	86.38	88.85
Source of variation			ANOVA results (*P>F*)							
Temperature (Temp)			0.086	0.000	0.001	0.000	0.188	0.004	0.492	0.000
Moisture (Mois)			0.625	0.220	0.002	0.431	0.541	0.670	0.057	0.105
Temp x Mois			0.578	0.922	0.324	0.522	0.112	0.971	0.478	0.018

Table II-6. The chenges in the values of $\delta^{13}C$ (‰) and their analysis of variance in the control bulk soil (C) and rice straw added soil (S) under 2 moistures and 4 temperatures regimes after 6, 12, 18 and 24 weeks incubation.

Tempe-rature	Soil moisture in WFPS	Code	6 weeks		12 weeks		18 weeks		24 weeks	
			C	S	C	S	C	S	C	S
±5 °C	60 %	L±5	-22.07	-23.24	-22.05	-23.16	-22.04	-23.09	-21.96	-22.93
	100 %	H±5	-22.10	-23.29	-22.17	-23.23	-22.03	-23.09	-22.02	-22.98
5 °C	60 %	L05	-22.03	-23.14	-22.13	-23.26	-22.08	-22.95	-21.98	-22.97
	100 %	H05	-22.02	-23.17	-22.17	-23.32	-22.06	-22.97	-21.99	-23.02
15 °C	60 %	L15	-22.12	-23.08	-22.16	-23.08	-22.02	-22.93	-22.01	-22.88
	100 %	H15	-22.10	-23.06	-22.15	-22.89	-21.99	-22.86	-22.01	-22.72
25 °C	60 %	L25	-22.05	-22.92	-22.07	-22.88	-22.03	-22.81	-22.00	-22.68
	100 %	H25	-22.07	-22.93	-22.02	-22.81	-22.02	-22.59	-21.98	-22.54
Source of variation			ANOVA results (*P>F*)							
Temperature (Temp)			0.062	0.000	0.026	0.000	0.150	0.000	0.738	0.000
Moisture (Mois)			0.747	0.484	0.804	0.481	0.290	0.007	0.511	0.232
Temp x Mois			0.706	0.793	0.606	0.195	0.968	0.025	0.398	0.105

aerobic incubation period were used to determine the total C left in the soil samples after SOC and rice straw C were decomposed out. Theoretically, the rates of rice straw decomposition should be the same using the three calculation methods if the inhomogeneity of SOC and isotope fractionation of straw decomposition could be ignored, but the results differed among the three methods. Though the decomposition rates of rice straw with all methods were strongly influenced by temperature and moisture in this study as in many previous studies (Shiga *et al*. 1985; Goto *et al*. 2004; Hassan *et al*. 2014; Zhou *et al*. 2014), the trends of decomposition rate with incubation time were different among the methods. The CO_2 production was measured every 2 weeks at the mg C kg^{-1} soil level, and the calculated decomposition rate of rice straw showed a steady change with incubation time, while the decomposition rates of rice straw calculated using SOC content and $\delta^{13}C$ value did not show such a consistent trend with incubation time. This difference should be caused by the measurement error in SOC and $\delta^{13}C$ analyses due to the high SOC content in bulk soil, as described above.

According to the value calculated from CO_2 production, decomposition rates of SOC and rice straw were significantly greater for 100% WFPS than for 60% WFPS. This result is not consistent with the other studies, which reported higher CO_2 emissions under intermediate moisture contents, e.g., 60% WFPS (Williams 2007; Suseela *et al*. 2012; Zhou *et al*. 2014). The CO_2 production was limited by O_2 depletion at higher soil moisture levels, especially under saturated conditions.

However, in this study, the oxygen was not limited due to enough O_2 availability and to the shallow soil layer (about 1 cm).

Straw decomposition rates in previous studies varied among soil types, moistures, temperatures and incubation times. Pal and Broadbent (1975) showed the importance of soil moisture for straw decomposition by microorganisms. Under their best soil moisture condition (60% of soil water holding capacity: WHC) enhancing straw decomposition, 74.4% of added-straw C was decomposed during a120-d incubation at 22 °C. Devêvre and Horwáth (2000) measured the decomposition rate of rice straw mixed with willow clay and showed that 54.8% of straw C was decomposed after 160 d of incubation at 25 °C and 50% of WHC. Compared to those above, the decomposition rate in this study is relatively lower, or similar in this study. Various conditions of incubation might change the rate of straw decomposition. Here, straw was ground and mixed into the soils which had high SOC contents. Despite the fact that mixing straw into soil might generally enhance decomposition, the decomposition rates in this study were lower than that of Goto *et al*. (2004), who used a type of litter-bag and incubated samples for 12 weeks at 20 °C, and obtained a decomposition rate of 55.5%. One obvious difference in this study is the high content of SOC. In previous studies, the SOC of bulk soils ranged from 12.6 to 20.7 kg^{-1} soil, while we used an Andisol containing 89.0 g kg^{-1}. There are some special characteristics of Andisol, a volcanic ash soil, which could be additional reasons for the retardation of straw decomposition. But details of the causes of retardation cannot be discussed with the results of this study.

With the value calculated from CO_2 production, rice straw decomposition rates under ±5 °C were low at 12.7 and 14.0% for low and high moisture conditions after 24 weeks' incubation, while the temperature condition was designed for the winter period of the off-rice season with freezing and thawing cycles in Tohoku district. The low decomposition rates indicate that most of incorporated straw was not decomposed in aerobic conditions in the fallow season under cold conditions. The remaining straw C could therefore become a substrate for methanogenic bacteria and thus enhance CH_4 emission during the next rice growing season. Concerning the mitigating aspects of CH_4 emission, the effect of temperature sensitivity of rice straw decomposition must be seriously considered, and management plans to promote the aerobic decomposition of crop residues during the relatively high-temperature period in the fallow season should be promoted.

The Q_{10} temperature coefficient corresponds to the rate of change for a biological or chemical system as a consequence of a 10 °C temperature increase. Here, we calculated Q_{10} for rice straw decomposition rates based on the three parameters of CO_2 production, SOC content and $\delta^{13}C$ value. Generally, the Q_{10} decreases with increasing temperature, while how moisture affects Q_{10} is controversial (Zhou *et al*. 2014). Though mean Q_{10} values of rice straw decomposition rates among the three calculation approaches were greatly different, the Q_{10} ranged from 1.17 to 7.11 (Table II-3). The reason for the high mean Q_{10}

values calculated from the $\delta^{13}C$ data, especially under high moisture and low temperature conditions, should be the low decomposition rate calculated for the early weeks under the ±5 °C temperature condition. All of the Q_{10} values obtained from the three calculation methods show a decreasing trend with increasing temperature, in accordance with previous studies (Luo *et al*. 2001; Zhou *et al*. 2014). The effect of moisture on Q_{10} in this laboratory incubation experiment was not clear and showed controversial results among different temperature ranges and different calculation methods.

2.6 CONCLUSIONS

For understanding how both temperature and moisture can affect the rate of rice straw decomposition during the off-rice season in the cold temperate region of Japan, a modeling incubation experiment was carried out in the laboratory. Among the three methods used to calculate the rate of rice straw decomposition, the method using CO_2 production measurement showed more accuracy compared to those based on the SOC content and its $\delta^{13}C$ value. Under the 100% WFPS condition, the rates of rice straw decomposition were 14, 22.2, 33.5 and 46.2% at -5 to 5, 5, 15 and 25 °C, respectively, while under the 60% WFPS condition, these rates were 12.7, 18.3, 31.2 and 38.4%, respectively. These values were lower than those reported in previous studies. The Q_{10} was higher between -5 to 5 and 5 °C than that between 5 and 15 °C and 15 and 25 °C. Daily freezing-thawing cycles (from -5 to 5 °C) did not stimulate rice straw decomposition compared with low temperature (5 °C). This study implies that to reduce CH_4 emissions from rice paddies during the single rice-growth season in cold temperate regions, improving rice straw decomposition during the high temperature period of the off-rice season is very important.

Chapter III:

Monitoring the effect of shallow autumn tillage to incorporate rice straw on CH_4 emission in the next rice growth season from an Andisol paddy field experiment in Morioka, a cold region of Japan

3.1 ABSTRACT

To mitigate CH_4 emission from paddy fields, accelerating the decomposition of the incorporated organic matter during the fallow season would be a practical strategy. Various ways to accelerate the decomposition rate have been proposed, but their effectiveness in cold regions has not been confirmed. Previous research suggested that shallow autumn tillage to incorporate rice (*Oryza sativa*) straw in the soil reduced CH_4 emission in the following growing season. In this study, the use of shallow autumn tillage to incorporate straw in the soil and its potential to mitigate CH_4 emission during the following rice growing season were evaluated in an Andisol paddy field in Morioka, a cool region in Japan. A *japonica* rice cultivar, 'Akitakomachi', was planted and grown from 2012 to 2014 under consistent conditions, but with two autumn tillage treatments: conventional (15 cm) and shallow (7 cm). CH_4 fluxes from the plots were measured using a closed-chamber method throughout the 3 years. Overall, CH_4 emission did not differ between the conventional and shallow tillage plots in this study. However, CH_4 emission differed greatly among the years, especially during early rice growth stages, and the differences were related to temperatures but not the soil moisture content during the previous fallow season. Simulation of water contents during the fallow period suggested that the percolation rate was sufficiently high to create more aerobic soil conditions during

the fallow season in both the conventional and the shallow autumn tillage treatments. These results suggest that the soil water was neither so high nor so low that it retarded rice straw decomposition in the fallow season. The results suggest that shallow autumn tillage will not necessarily reduce CH_4 emission during the following growing season in an Andisol rice paddy in a cold region in Japan.

3.2 INTRODUCTION

Rice (*Oryza sativa*) straw incorporated in the soil of paddies becomes an important source of CH_4 emission when aerobic decomposition is impeded. Through a pot experiment with ^{13}C-enriched soil and rice straw, Watanabe *et al*. (1999) showed that the contribution of each organic source to emitted CH_4 changed over time. During the early stages of the rice growing period, 80% of total CH_4 emitted from the rice paddy field is derived from the incorporated rice straw's carbon, but the contribution of rice straw carbon decreased over time, reaching 20% of the total emitted CH_4 at 60 days after transplanting. Many previous studies showed that CH_4 emission increased when rice straw was incorporated into a paddy soil (Schütz *et al.*, 1989a; Yagi and Minami, 1990; Sass *et al*., 1991; Watanabe *et al*., 1994; Naser *et al*., 2007; Eusufzai *et al*., 2011; Alberto *et al*., 2015). Not only the amount, but also the timing and form of the incorporated straw greatly affect CH_4 emission. For example, many researchers reported that direct straw incorporation without composting could cause large CH_4 emission in the following summer (Yagi and Minami, 1990; Wassmann *et al.*, 2000b), as was the case for spring incorporation of straw just before rice transplantation (Inubushi *et al.*, 1994; Yagi *et al.*, 1997; Wassmann *et al.*, 2000b; Goto *et al.*, 2004; Zhang *et al.*, 2013). These results suggest that CH_4 emission during the current rice growing season could be decreased by promoting aerobic straw decomposition during the previous fallow season. However, in recent decades, plant residues have commonly been scattered on the soil surface during harvesting with a combine harvester rather than being composted. Although composting of the straw before use could mitigate the CH_4 problem, this would be expensive and labor-intensive. Thus, in a single-cropping system, which is commonly used in cold areas such as the Tohoku region of northern Japan, the residues often experience aerobic decomposition at the soil surface or inside the near-surface layer during the winter fallow season. Less-expensive and easier ways to accelerate the decomposition of surface or soil-incorporated straw during the fallow season are needed.

To increase the decomposition of rice straw during the fallow season, researchers have evaluated many strategies, such as adding a decomposition accelerator during straw incorporation (Goto *et al*., 2004; Minamikawa *et al*., 2005; Han and He, 2010; Zhang *et al*., 2013), drying the field naturally or by means of artificial drainage (Cai *et al*., 2003; Shiratori *et al*., 2007; Xu and Hosen, 2010; Sander *et al*., 2014), and no-tillage rice cultivation (Hanaki *et al*., 2002). As a potential new strategy, shallow-soil incorporation of organic matter in the autumn after harvesting has been proposed. Matsumoto *et al*. (2002) compared the CH_4 flux from paddies in which cow manure was incorporated in autumn at shallow and conventional depths (3 and 15 cm, respectively). They found that shallow incorporation of cow manure in autumn decreased the CH_4 flux during most of the following growing season and that the cumulative CH_4 emission during the growing period in the shallow tillage plot was about 70% of that in the conventional management. They concluded that shallow incorporation of organic matter into the soil in autumn accelerated aerobic decomposition. Though they did not discuss a mechanism for the accelerated degradation of the organic matter, it is reasonable to hypothesize that the tillage depth affected the soil's water conditions (e.g., by improving drainage of the surface layer), which critically determine the amount of oxygen available to support aerobic decomposition. Doberman and Fairhurst (2002) also mentioned the advantages of early and dry shallow tillage (5 to 10 cm in depth) for mitigation of CH_4 emission. They proposed that the advantages resulted from enhanced soil aeration, which accelerated aerobic decomposition of the incorporated rice straw. This option for CH_4 mitigation is attractive because it requires little additional cost to adopt and it may have great advantages if the mechanisms, effects, and range of applicable field conditions can be understood.

Tohoku is a relatively cold region of Japan, with a mean annual temperature of about 10.5 °C and mean monthly temperatures ranging from –1.9 °C in January to 23.4 °C in August. This region contains 25% of the area of Japanese rice paddies and yields 28% of

Japan's domestic rice production (MAFF, 2015). Hayano *et al.* (2013) estimated national-scale CH_4 emission in Japan and showed that 54% of domestic CH_4 emission from rice paddies (more than double the amount that would be expected on an area basis) was emitted in Tohoku region. They concluded that the characteristic climate and soils in Tohoku region should be a cause of this high CH_4 emission rate. As shown in Chapter II, temperature has a large effect on the organic matter decomposition rate. The relatively low temperature during the fallow season in this region may decrease the rate of aerobic decomposition of rice straw. The higher quantity of the undecomposed organic matter at the start of the following rice growing season would then increase CH_4 emission. However, there have been no studies of the relationships between field conditions (such as soil moistures content and temperatures during the fallow season) and CH_4 emission in the following rice growing season at a field scale.

Thus, the present study had two goals: to identify the relationships between the field conditions during the fallow season and CH_4 emission in the following summer, and to evaluate the effect of shallow tillage in autumn for mitigation of CH_4 emission.

3.3 MATERIALS AND METHODS

3.3.1 Study Site and Rice Cultivation

A field experiment was performed in a well-drained paddy field at the Agricultural Research Center for Tohoku Region of the National Agricultural Research Organization (TARC/NARO) in Morioka, Japan (39°74′N, 141°13′E). The soil is an Andisol with a silty clay loam texture according to the International Union of Soil Science classification and had a high soil organic carbon content. Table III-1 summarizes the soil's properties. The water infiltration rate in the experimental field was high enough for 50 mm of water to drain daily under flooded conditions. Two different autumn tillage depths were compared: shallow (7 cm) and conventional (15 cm). Each treatment had three replicates, using 13.2-m^2 plots (4.4 m × 3 m).

Table III-1. Major soil properties (to a depth of 10 cm) at the study site

Soil type	Andisols
Bulk density (Mg m^{-3})	0.60
Soil texture (%)	
Clay	19.09
Silt	33.42
Sand	47.49
Organic C (g kg^{-1} DW)	89.0
Total N (g kg^{-1} DW)	6.7
C/N	13.3
pH (1:2.5 H_2O)	6.73

All the plots were tilled to a depth of 15 cm on 9 May 2012, before the research began, using a rotary tiller to prepare them for transplanting of the rice seedlings. The experiment was conducted from 2012 to 2014. Table III-2 summarizes the dates of the primary treatments in each of the 3 years of the study. After drainage of the field and harvesting of the grain, all the test plots in each treatment were tilled to the specified depth using a rotary tiller in October. During this autumn tillage, 580 g m^{-2} (air-dried basis) of shredded rice straw (cut to 5 cm in length) was incorporated into the soil in both treatments. The total organic carbon in the incorporated rice straw was 373.7 g C kg^{-1} with a C/N ratio of 52.0. The fields were then left under natural conditions until the following spring. In May, all the plots were tilled again to a depth of 15 cm using a rotary tiller to prepare them for transplanting of the rice seedlings. Fertilizer was applied at the same time as the spring tilling, as a basal dressing of 9 g m^{-2} of N (6 g N m^{-2} as urea and 3 g N m^{-2} as ammonium sulfate), 30 g m^{-2} P_2O_5 equivalent, and 15 g m^{-2} K_2O equivalent. Flooding started within 1 day after the spring tillage, and soil was puddled to level the field for transplanting and to decrease vertical infiltration. Seedlings of 'Akitakomachi', a popular *japonica* rice cultivar in the Tohoku region, were transplanted in late May of each year at a planting density of 19 plants m^{-2} (with a row width of 30 cm and an intra-row spacing of 17.5 cm). Flooding was maintained until early to mid-September, without a mid-season drainage. After about 140 days of growth, the rice grain was harvested in early October, and all of the straw was removed from the test plots. The straw was then cut into 5-cm lengths and stored in a screen house until it could be scattered on the soil surface just before the next autumn tillage.

Table III-2. Management regimes during the 3-year field experiment

	Management date (year/month/day)		
	2012	2013	2014
Autumn application of rice straw	2011.10.13	2012.10.29	2013.10.15
Autumn tillage	2011.10.13	2012.10.29	2013.10.15
Spring flooding of the field	2012.05.09	2013.05.09	2014.05.16
Spring tillage	2012.05.09	2013.05.09	2014.05.15
Rice transplanting	2012.05.22	2013.05.29	2014.05.27
Rice heading	2012.07.31	2013.08.06	2014.07.28
Drainage	2012.09.11	2013.09.17	2014.09.12
Harvest	2012.10.11	2013.10.03	2014.10.08

3.3.2 Measurement of CH_4 Fluxes

In all 3 years, the CH_4 fluxes from the paddy fields were measured using a closed-chamber method (Yagi *et al*., 1991). The measurement frequency was monthly during the fallow season and weekly or biweekly during the rice growing season. On each sampling day, gas in an acrylic plastic chamber (60 or 120 cm high, with a basal area of 60 cm × 35 cm) was sampled with a plastic syringe at 0, 10, and 20 minutes after installation of the chamber. Sampling was carried out between 09:00 and 12:00 throughout the experimental period. The chamber was installed carefully to avoid soil disturbance and gas leakage in both the rice growing season and the fallow season. For the rice growing season, four pairs of a rod and a clamp were set to the paddy field in line with the chamber basement immediately after transplanting. And on each sampling day, the chamber was set on the clamps gently as shown in Figure III-1. The lower end of the chamber was positioned below the surface of the paddy water, and the water level in the chamber was measured to allow calculation of the chamber volume. The chamber was positioned to cover four rice plants. For the fallow season without surface ponding water, a square metal frame with H-shaped section was installed to a depth of 10 cm in the soil immediately after drainage. During the sampling of gas, the chamber was set on the frame which filled with water to prevent gas leakage (Fig. III-1). Air temperature inside the chamber was measured using a digital thermometer attached to the inner wall. The sampled gas was injected into 20-mL glass vacuum vials and brought back to the laboratory for analysis. The concentration of CH_4 in the vials was analyzed using a gas chromatograph equipped with a flame ionization detector (GC-8A, Shimadzu Corporation, Kyoto, Japan). The efflux rate (E; mg C m^{-2} h^{-1}) of CH_4 was calculated based on the concentration increase during the sampling time, as follows:

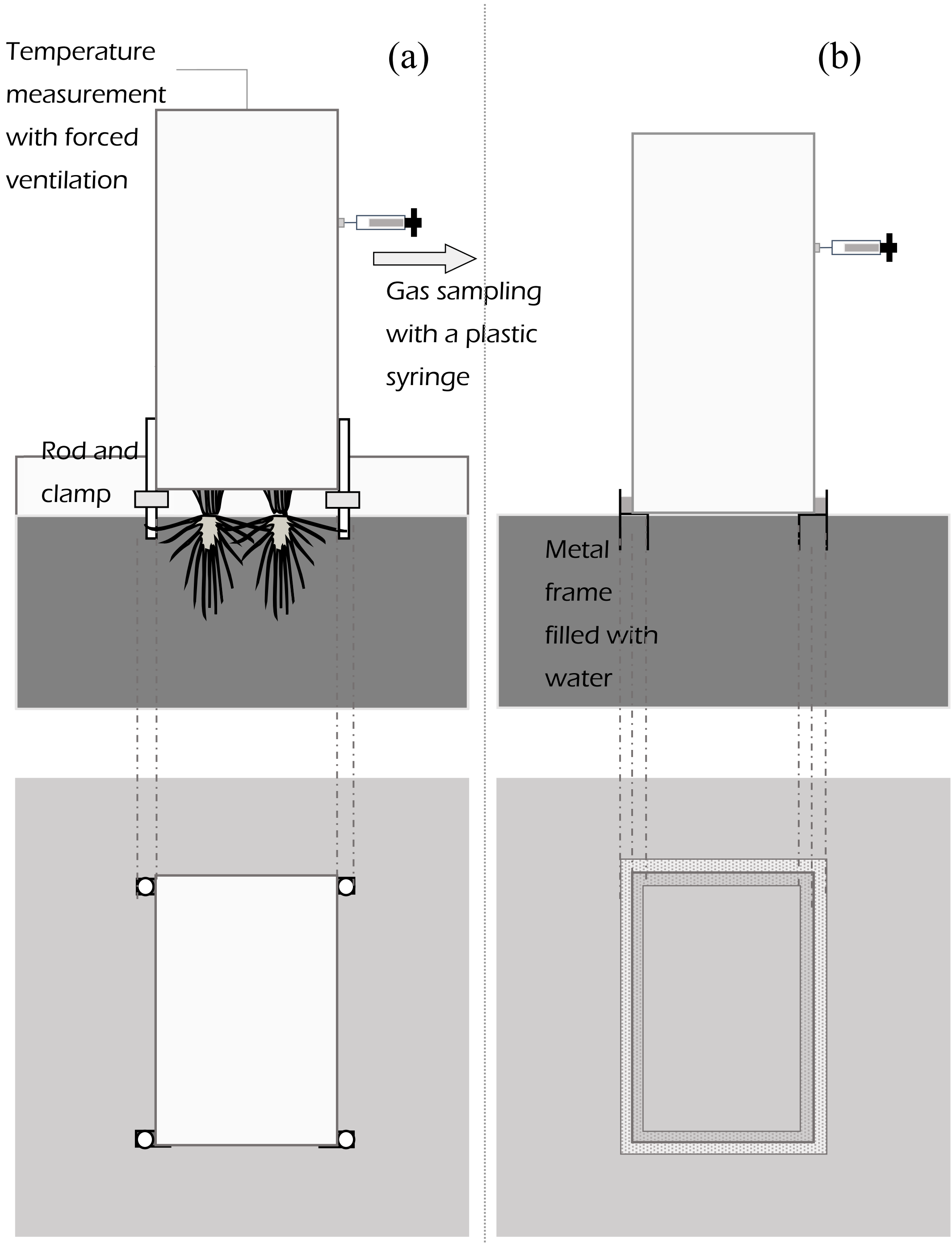


Fig. III-1. Schematic lateral and top views of chamber settlement and gas sampling in (a) the rice growing season and (b) the fallow season from the experimental field. An acrylic plastic chamber was set carefully on the field avoiding soil disturbance and gas leakage.

$$E = \frac{\Delta C}{\Delta t} \times M_c \times P \times V \times \frac{1}{RT} \times \frac{1}{A} \quad (1)$$

where $\Delta C / \Delta T$ is the change in the concentration of CH_4 ($m^3\ m^{-3}\ h^{-1}$) in the chamber during a given period (h); V is the chamber volume (m^3); P is standard atmospheric pressure (101.325 kPa), M_c is the molar mass of carbon (12.0×10^3 mg mol^{-1}); P is standard atmospheric pressure (101.325 kPa); V is the chamber volume (m^3); R is the universal gas constant (8.314 m^3 Pa K^{-1} mol^{-1}); T is the absolute temperature in the chamber (K); and A is the cross-sectional area of the chamber bottom (m^2). Flux calculation was based on the assumption of a constant flux during sampling time. The cumulative emission during a specific period was calculated based on the assumption of a linear change in the CH_4 flux between sampling dates.

3.3.3 Calculation of Soil Water Content

To evaluate the effects of soil water content on the decomposition of rice straw, the change in the soil water saturation (S, the volumetric ratio of water-saturated pore space to total pore space in the soil) after the field drainage was calculated using version 4.16.0090 of the HYDRUS-1D software (Simunek *et al.*, 2008). This simulation is based on Richard's equation and accounts for water flow, vapor flow, snow hydrology, and heat transport. Root water uptake was not considered because no plants were present during the fallow season. Daily meteorological parameters such as air temperature, humidity, rainfall, wind speed, and daylight hours were monitored at the TARC/NARO weather station near the test plots. Based on the meteorological data, potential evaporation was calculated using the Penman-Monteith equation (Monteith, 1981). The van Genuchten -Mualem formula (van Genuchten, 1980), with an air-entry value of –2 cm, was applied to determine the soil hydraulic properties. The volumetric water content (θ) at a given hydraulic head (h), θ(h), was calculated as follows:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \qquad \text{for } h - h_r < 0 \qquad (2)$$

$$\theta(h) = \theta_s \qquad \text{for } h - hr \geq 0 \qquad (3)$$

where θ_r and θ_s are the residual and saturated water contents (dimensionless), respectively. h_s is the air-entry value (–2 cm), and α (cm^{-1}), m (dimensionless), and n (dimensionless) are empirically derived parameters. Hydraulic conductivity, $K(S_r)$, was calculated as follows:

$$K(S_\mathrm{r}) = K_\mathrm{s} \times {S_\mathrm{r}}^{L} \times \left\{1 - \left[1 - {S_\mathrm{r}}^{\frac{1}{m}}\right]^{m}\right\}^{2} \tag{4}$$

where K_s is the saturated hydraulic conductivity (cm day^{-1}); S_r is the relative saturation, which is calculated as $S_\mathrm{r} = \frac{\theta(h)-\theta_\mathrm{r}}{\theta_\mathrm{s}-\theta_\mathrm{r}}$, and L is an empirically derived pore tortuosity and connectivity parameter (dimensionless). Soil parameters in the model equations, except for the air-entry value and L (set to a uniform value of 0.5), were estimated using Rosetta Lite (Schaap *et al.*, 2001), a neutral-network-based function coupled with HYDRUS-1D, using the measured particle size distribution and dry bulk density of the soil in the test plots (Table III-1). The boundary condition at the bottom of the soil profile was set to free drainage at a depth of 100 cm. The thermal conductivity of the soil was calculated with a function proposed by Chung and Horton (1987).

In the simulation, the simulated soil profile with a depth of 100 cm was divided into three or four layers with different hydraulic parameters based on the different tillage and puddling histories (Fig.III-2). In the paddy field, a plow pan develops as a result of repeated tillage and puddling. This layer with low hydraulic conductivity remains in the soil profile until the following tillage. Thus, four layers with different hydraulic parameters were defined in the simulated soil profile during the period from the removal of ponding water to the autumn tillage: tilled, plow pan, not-tilled, and deep subsoil. For the period after the autumn tillage, the soil profile was divided into three layers: tilled, not-tilled, and lower subsoil. The deep subsoil layer was assumed to have a higher dry bulk density than the upper layers because of the soil compaction created by machine and human traffic. To estimate the parameters using Rosetta Lite, an assumed value of 2.0 Mg m^{-3} was used for the dry bulk density of the plow pan layer rather than using a measured value.

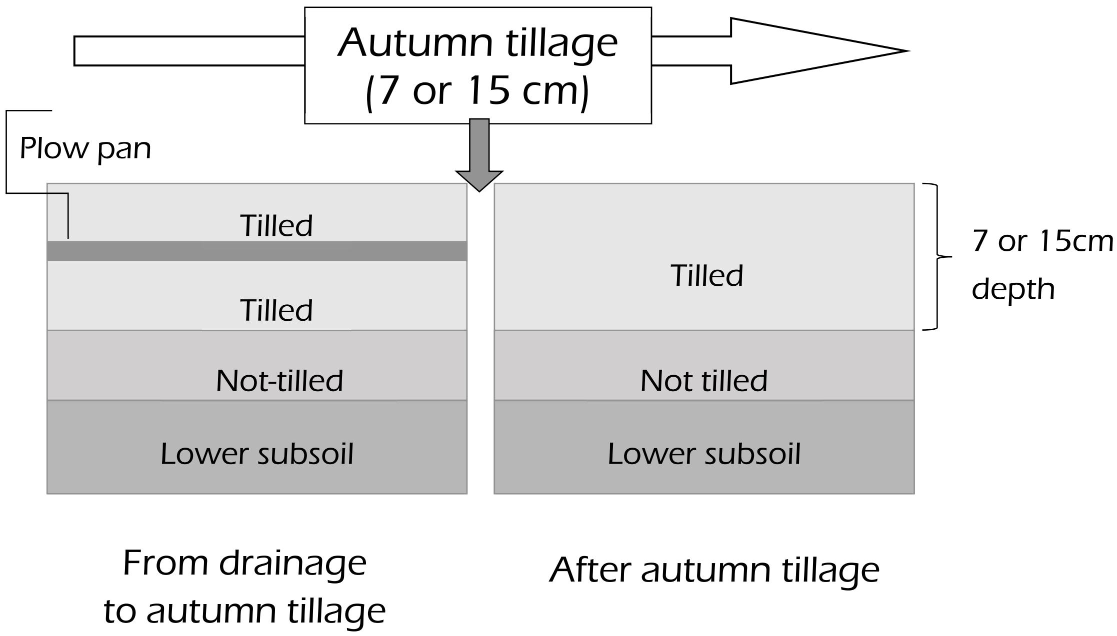


Fig. III-2. The segmentation of soil profile for simulation of soil water content using HYDRUS-1D. The ‘plow pan’ was assumed to be destroyed completely by the autumn tillage.

3.3.4 Statistical analysis

Statistical analyses were carried out using version 3.2.0 of the R software (R Core Team, 2015). Simple comparisons of CH_4 fluxes between the tillage treatments were performed using Student's *t*-test for each sampling day. The effects of tillage treatments and test years on the cumulative CH_4 emission during the first 60 days of the rice growing season and during the total rice growing season were tested by two-way repeated-measures analysis of variance. Simple regression analyses were performed to investigate the effects of soil temperature and moisture in specific periods on CH_4 emission from the paddy field.

3.4 RESULTS AND DISCUSSION

3.4.1 Temperature Trends during the Study Period

Table III-3 shows the mean monthly air temperature during the experimental period and the normal values based on data from 1981 to 2010. Compared with the normal values, air temperatures during the experimental period tended to be higher in the summer (June to September) and lower in the winter (November to February).

Table III-3. Monthly mean air temperature during the study period and normal values (1981-2010)

	2011	2012	2013	2014	normal value*
January	-4.6	-4.4	-4.3	-3.3	-2.8
February	-1.4	-4.6	-3.6	-2.5	-2.2
March	0.5	0.7	1.6	1.6	1.4
April	7.0	7.8	7.0	8.3	8.1
May	13.4	14.0	13.1	14.9	13.4
June	18.7	17.8	19.6	20.2	17.8
July	23.7	22.3	21.8	22.7	21.3
Augst	23.5	25.2	23.5	22.7	22.9
September	19.4	22.5	19.1	17.1	18.2
October	11.8	12.7	13.3	11.1	11.5
November	6.8	5.8	5.0	5.9	5.3
December	-0.8	-1.4	0.6	-1.8	0.3

* Data from Japan Meteorological Agency

3.4.2 Changes in CH_4 flux during the Study Period

Figure III-3 shows the changes in CH_4 fluxes from the test plots and in daily air temperature during the study period. In all 3 years, CH_4 flux decreased to zero during the winter fallow season, whereas some previous studies reported that poorly drained fields showed positive CH_4 fluxes even during the fallow season (Xu and Hosen, 2010; Sander *et al*., 2014). In this study, CH_4 was not emitted in the winter fallow season due to the high water permeability in the experimental field (an infiltration rate of 50 mm day^{-1} under flooded conditions). The CH_4 flux started to appear after ponding of the surface water, increased with plant growth, and reached a peak from July to August. After drainage in the early autumn, the CH_4 flux decreased immediately. In the conventional tillage treatment, the maximum fluxes reached 13.24, 11.96, and 7.91 mg C m^{-2} h^{-1} in 2012, 2013, and 2014, respectively, whereas the shallow tillage treatment produced maximum values of 11.76, 10.73, and 10.03 mg C m^{-2} h^{-1} (Fig. III-3a, b, c). The values in both tillage treatments are lower than those in previous studies in Japan, which used soils other than the Andisol of the present study (Yagi and Minami., 1990; Matsumoto *et al*., 2002; Goto *et al*., 2004; Minamikawa *et al*., 2005; Shiratori *et al*., 2007). The lower CH_4 efflux could be due to specific properties of Andisols, such as their high water permeability (Yagi and Minami., 1990; Hayano *et al*., 2013). On each sampling day during the 3-year experiment, there was no significant difference in CH_4 flux between the two tillage treatments ($p>0.05$).

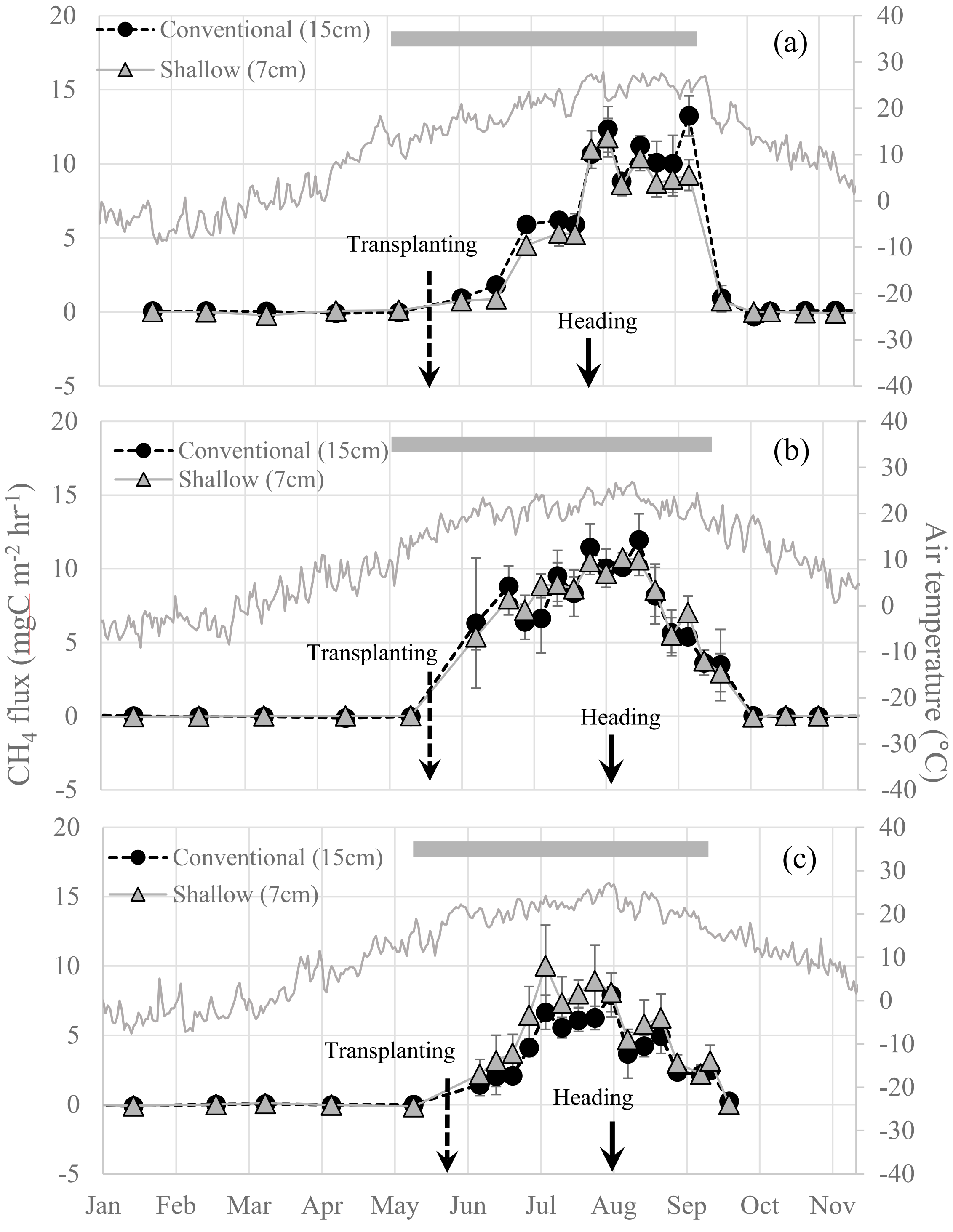


Fig.III-3. Changes in methane (CH_4) flux from the study plots and in mean daily air temperature in (a) 2012, (b) 2013 and (c) 2014. Values are means ± standard errors (n =3).

3.4.3 Effect of Shallow Tillage on CH_4 Emission

Based on the results of Watanabe *et al*. (1999), it is reasonable to hypothesize that the effects of carbon derived from rice straw on CH_4 emission would be clearer during the first 60 days of the rice growing season, before the contribution of organic matter produced by the new plants became significant. According to this assumption, the cumulative CH_4 emission during the first 60 days after transplanting (DAT) was calculated and compared with the emission during all the period of the rice growth season (Figure III-4). The CH_4 emission during the first 60 DAT (Fig. III-4b) accounted for 20 to 50% of the total for the growing season (Fig. III-4a). The cumulative CH_4 emission from the test plots differed significantly among years (p = 0.006) but not between the depth of autumn tillage for both the total CH_4 emission (p=0.94) and CH_4 emission during the first 60 DAT (p=0.82). Previous studies showed that the aerenchyma of rice plants act as a main route of CH_4 emission from paddy soil to the atmosphere (Cicerone and Shetter, 1981; Nouchi *et al.*, 1990). Additionally, plant growth or development of aerenchyma had been reported to affect the CH_4 emission rate from the paddy field (Watanabe *et al.*, 1994). Grain yield is one of the plant growth parameters that is strongly positively correlated with CH_4 flux from the field (Singh *et al.*, 1998). In the present study, the grain yield from the test plots (data not shown)

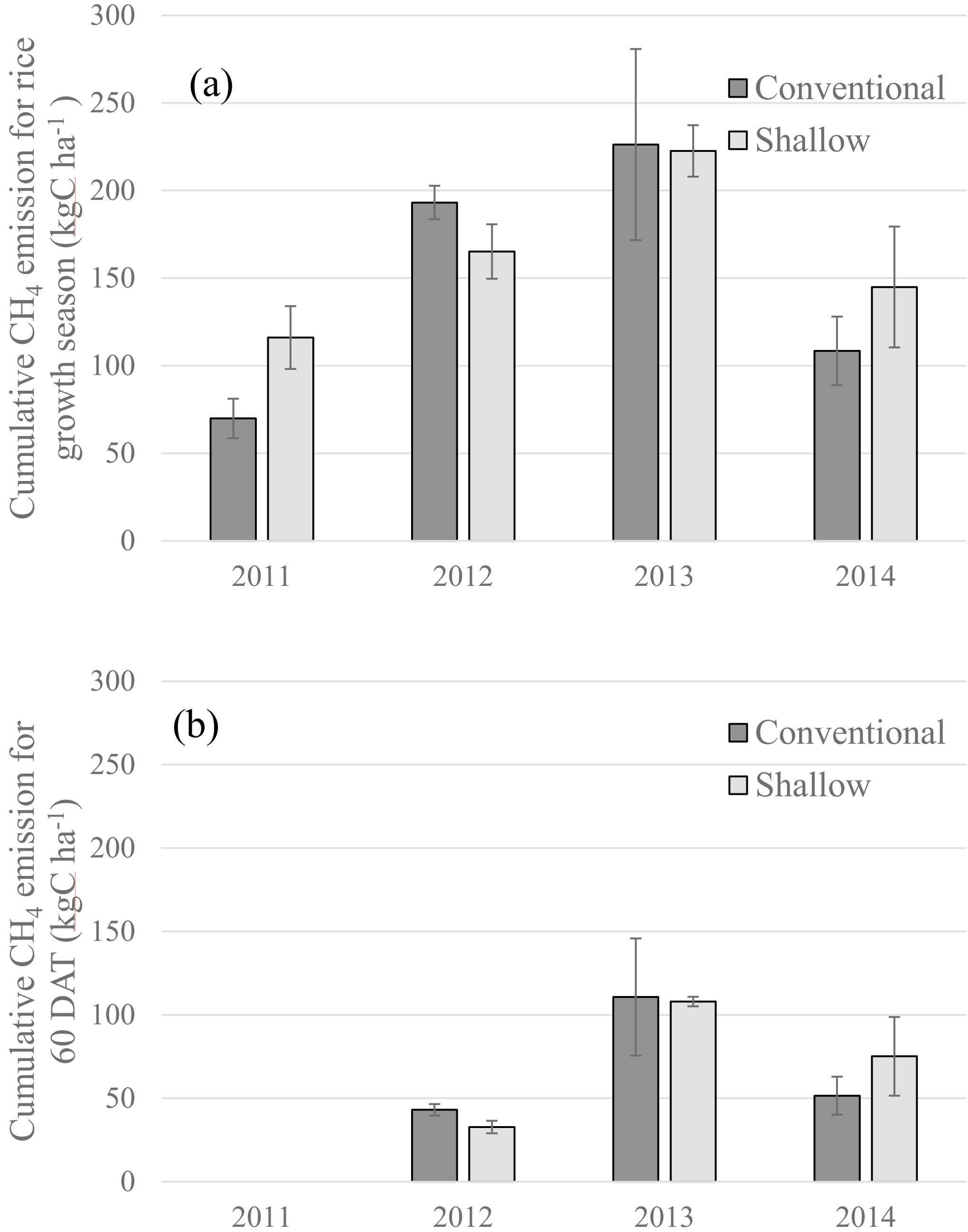


Fig. III-4. Cumulative methane (CH_4) emission from conventional and shallow tillage plots during (a) the whole rice growing season and (b) the 60-days period after rice transplanting. Bars indicate the standard errors (n= 3).

differed significantly among years (p<0.001), but not between the tillage treatments (p=0.59). In addition, there was a weak and non-significant positive correlation between grain yield and CH_4 emission in the conventional tillage treatment (R^2=0.46, p=0.14). Thus, it is possible that differences in plant growth were responsible for differences in the CH_4 emission between years. However, the coefficient of variation for the difference between years was higher for CH_4 emission during the first 60 DAT (0.47) than for the total CH_4 emission (0.26). This result indicates the existence of the other factors besides plant growth that differed between years and that should affect CH_4 emission from the paddy field, especially during the early growing season.

3.4.4 Effect of Temperature on CH_4 Emission

Higher temperatures during the growing season can increase CH_4 emission by promoting both the activity of methanogens and plant growth (Schütz *et al.*, 1989a; Hosono and Nouchi, 1997). To clarify the effect of temperature on CH_4 emission, the cumulative soil temperatures during the first 60 DAT were used as representative values for the rice growing season. Figure III-5a shows a weak and non-significant relationship (R^2 = 0.20, p=0.37) between cumulative CH_4 emission during the first 60 DAT as a function of the cumulative soil temperature during the same period, despite a relatively

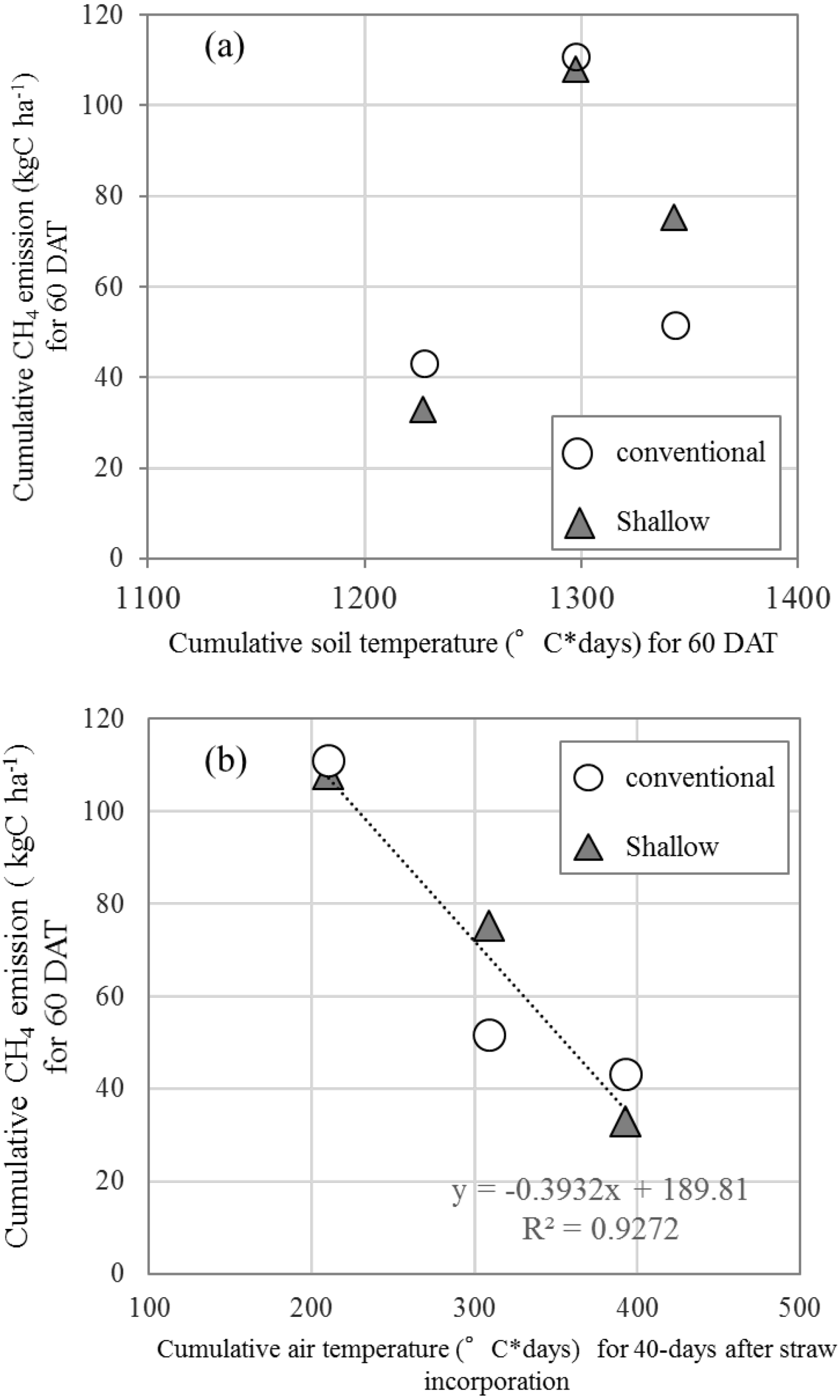


Fig. III-5. Relationships of methane (CH_4) emission during the first 60 days after transplanting (DAT) and (a) cumulative soil temperature during the first 60 DAT and (b) cumulative air temperature during the first 40 days after straw incorporation in the soil (DAI) during the previous year.

large difference between years in the cumulative temperature. This result contradicts previous researches (Schütz *et al*., 1989a; Hosono and Nouchi, 1997) that suggested a relationship between daily soil temperature and CH_4 flux in a gas sampling day during the growing season. Compared with the values in these previous studies (5 to 80 mg C m^{-2} h^{-1}), CH_4 flux observed in this study was very lower. In addition, Schütz *et al* (1989) found two or more clear peaks in CH_4 flux during a single growing season without a mid-season drainage; in the present study, only one peak was visible in all 3 years (Fig. III-3). They concluded that these peaks reflected the availability of substrates for methanogens: the first peak, during the vegetative growth period of rice, was caused by organic matter incorporated before the flooding, and the second or third peaks (during the rice reproductive stage) were due to plant-derived carbon such as root exudates or decayed tissues. They also found no correlation between CH_4 emission rates and soil temperature during a period when substrates for microorganisms were deficient in the soil. Combining these findings suggests that other factors than temperature which limited methanogenesis during the early half of the growing period in this experiment, possibly including a deficiency of substrates derived from incorporated organic matter.

Temperature and moisture are the two most important factors that affect the decomposition rate of rice straw in the soil (Sain and Broadbent, 1977; Devêvre and

Horwáth, 2000). To evaluate the effect of temperature on the straw decomposition rate and thus on CH_4 emission during the following growing season, the cumulative air temperature after the incorporation of rice straw in the soil was calculated. Though the actual soil temperature in the test plot was measured, the large size of the soil clods produced by the autumn tillage prevented accurate measurements. To avoid the effects of the resulting measurement errors on the results and to clarify the overall trends, air temperature was used instead of soil temperature in the subsequent analysis during the fallow season.

Previous research showed that the decomposition of easily mineralizable carbon in rice straw proceeds quickly during the first few months after its incorporation into the soil (Pal *et al*., 1975; Sain and Broadbent, 1977). Similarly, In the 24-week incubation study described in Chapter II, 39 to 63% of the organic matter mixed into an Andisol decomposed during the first 6 weeks. Based on these results, cumulative temperatures during the first 40 days after rice straw incorporation into the soil (DAI) were used as representative temperatures during the fallow season that might affect the decomposition rate of the incorporated rice straw. Figure III-5b shows a strong and statistically significant negative relationship ($R^2 = 0.93$, $p < 0.01$) between cumulative CH_4 emission during the first 60 DAT and the cumulative air temperature during the first 40 DAI during the previous fallow season. This suggests that temperature conditions during aerobic decomposition of the rice straw were an important factor that affected the degree of straw decomposition (i.e., that affected the amount of straw remaining at the end of the fallow season) and thus the CH_4 emission during the early period of the following growing season. This result also shows that high temperatures during the period just after the incorporation of rice straw into the soil could decrease early emission of CH_4.

3.4.5 Estimation of Water Regime Changes during the Fallow Season

Figure III-6 shows the simulated changes in soil *S* at a depth of 5 cm after drainage in the conventional tillage plot (Fig. III-6a) and the shallow tillage plot (Fig. III-6b). Autumn tillage was performed on day 0 in each year and occurred 30 to 50 days after field drainage in all years (Table III-2). Immediately after removal of the surface water, *S* decreased sharply in both tillage plots, decreasing from a value between 0.8 to 0.9 to a value between 0.4 to 0.6 within 5 days, although there was fluctuation as a result of rainfall during the simulation period. *S* stabilized at values of 0.4 to 0.6 by the day of the autumn tillage. Because rice straw was removed from the field before the autumn tillage, the water content of the soil was relatively low when rice straw was incorporated. There was no obvious difference in *S* between the shallow and

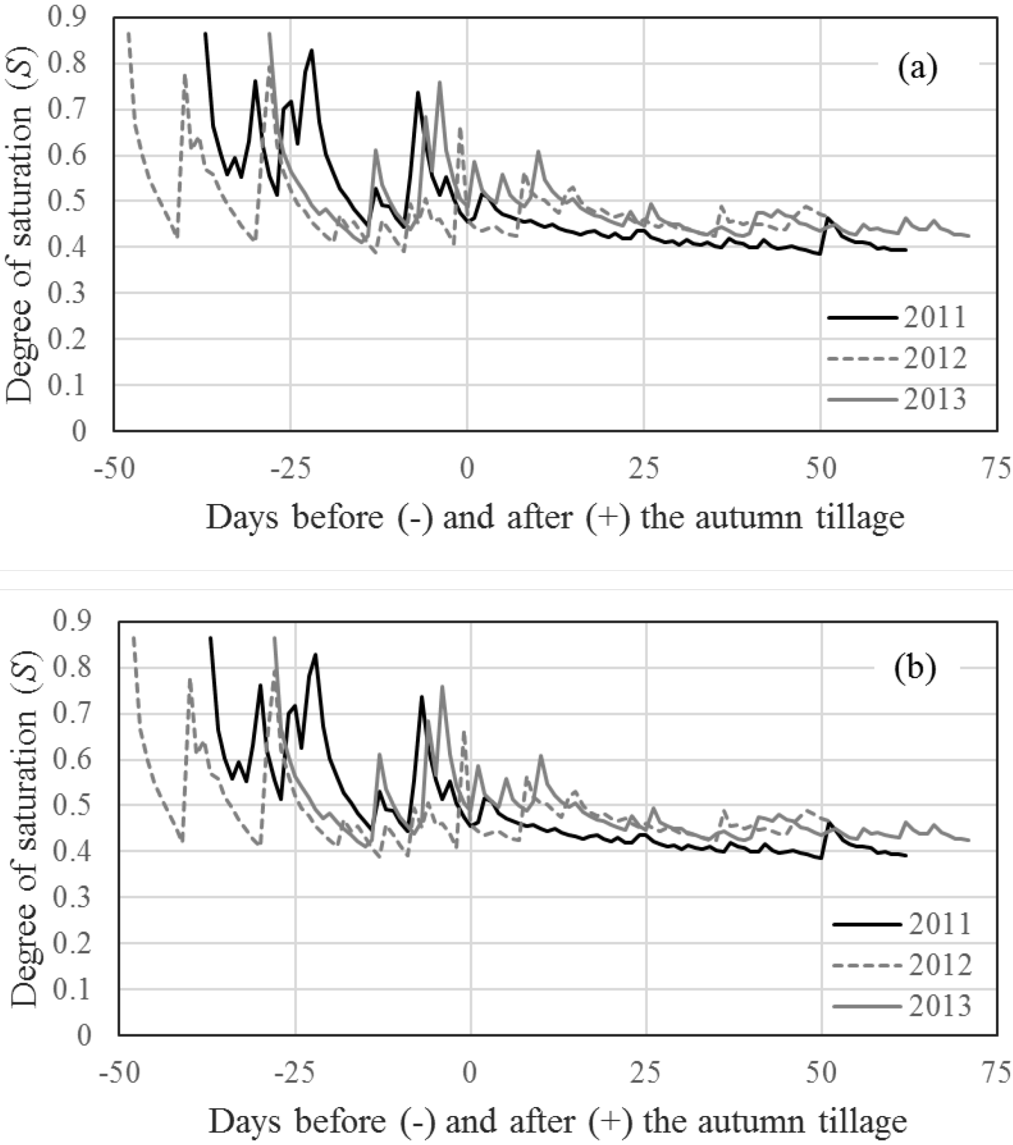


Fig. III-6. Changes in the calculated water saturation (*S*) of the paddy soil aft the depth of 5 cm in (a) the conventional tillage (15 cm) plot and (b) the shallow tillage (7 cm) plot. Each line starts at the day of field drainage. At day 0 in each year, the autumn tillage was performed.

conventional tillage plots even after the autumn tillage (Fig. III-6); the maximum differences in *S* values between the two tillage depths around the time of the autumn tillage were 0.001. Figure III-7 shows the relationships between cumulative CH_4 emission during first 60 DAT and mean *S* for the first 40 DAI in the previous year. There was no significant relationship (R^2 = 0.26, p=0.30). This result implies that the soil water regime has little effect on rice straw decomposition in the autumn and thus on cumulative CH_4 emission in first 60 DAT of the following season. This may be because the range of *S* values during the 3 years was very small (about 0.05), and may

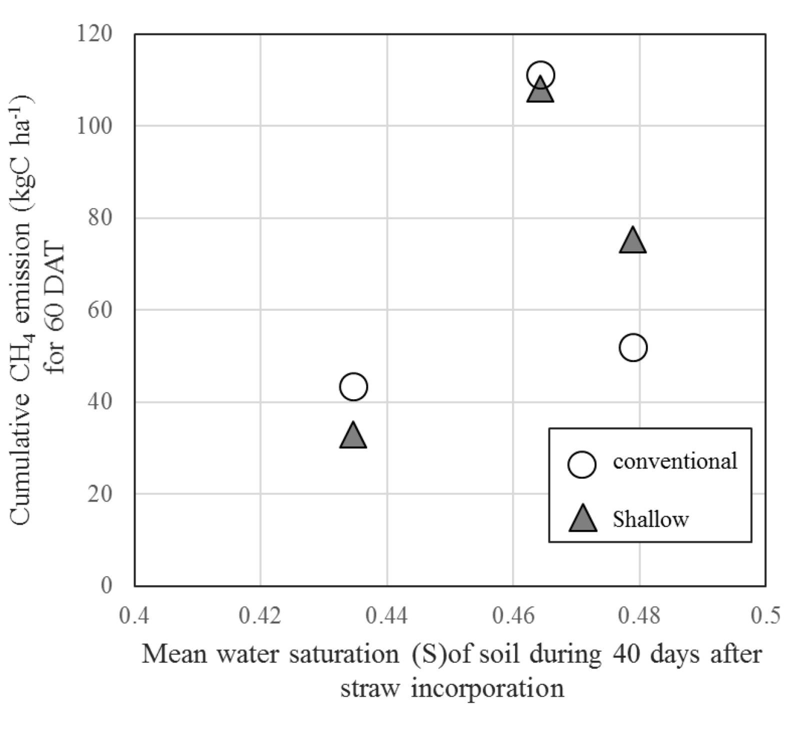


Fig. III-7. Relationship between cumulative methane (CH_4) emission during the first 60 days after transplanting (DAT) and the calculated mean water saturation (*S*) for the first 40 days after incorporation of straw (DAI) during the previous year.

have been too small to have a significant effect. This small difference may have resulted from a characteristic of the experimental field, such as its high water permeability. Previous studies investigated the optimal soil water conditions to increase the aerobic decomposition of incorporated rice straw. Pal and Broadbent (1975) performed an incubation experiment and found that 60 % water holding capacity (WHC) decomposition of the incorporated straw increased compared to decomposition at WHC of 30% and 150% WHC. They deduced that the microbial activities that affect the rate of decomposition of organic matter under conditions with too-low (30% WHC) and too-high (150% WHC) soil water content would be suppressed because of the shortage of water and oxygen, respectively. Xu and Hosen (2010) showed that WHC of 38 to 59% in the fallow season was optimal to decrease CH_4 emission in following rice growing season through a pot experiment. They proposed that the water regime in the fallow season affects the soil's oxidation capacity and this, in turn, affects the decomposition rate of organic matter during the fallow season and the CH_4 emission in the following rice growing season. WHCs values in these studies were equivalent to *S* (in percent terms) in the present study. Compared with these results, the soil water conditions in the fallow season in the present study (40 to 60% WHC) seemed to be almost optimal for the decomposition of organic matter.

This suggests that there was no inhibition of aerobic decomposition of the incorporated straw by excess or insufficient soil water in either tillage treatment.

The higher water permeability in the experimental field could explain the inability of the shallow autumn tillage to mitigate CH_4 emission. If the shallow autumn tillage decreases CH_4 emission during the next rice growing season by decreasing the soil water content in the layer where the straw is incorporated and improves aerobic decomposition of the incorporated rice straw, the effectiveness of this practice should depend on the soil water regime in the field during the fallow season. That is, shallow tillage would only mitigate CH_4 emission in a field where excess water would slow straw decomposition during the fallow season.

3.5 CONCLUSIONS

A continuous 3-year field experiment was performed in a paddy field in a cold region of Japan to determine the effects of the depth of autumn tillage to incorporate rice straw into the soil on CH_4 emission in the following growing season. The soil of the experimental field was an Andisol with high permeability. During the study period, shallow tillage in autumn had no significant effect on CH_4 emission during the following growing season. Cumulative CH_4 emission during the first 60 DAT, which is likely to be affected primarily by the organic matter incorporated in the soil during the previous autumn, depended strongly and significantly on the cumulative air temperature during the 40 DAI in the previous year. On the other hand, the simulated soil water content during the 40 DAI was not correlated with the cumulative CH_4 emission during the first 60 DAT in the following rice growth period. Simulation of soil water content in the experimental field using the HYDRUS-1D model indicated that the soil water content was relatively low when the rice straw was incorporated into the soil; thus, it is unlikely that aerobic decomposition of the straw was inhibited by soil excess water in any year. The present results suggest that shallow autumn tillage to mitigate CH_4 emission during the rice growing season would only be effective if too much soil water was present to allow rapid decomposition and shallow tillage increased aerobic decomposition. This suggests that the ability of this practice to mitigate CH_4 emission from rice paddy fields will depend on the field moisture conditions in the previous fallow season.

Chapter IV:

Modelling the effect of autumn tillage on CH_4 emissions from six rice paddies around Japan by DNDC-Rice model

4.1 ABSTRACT

For estimating the effect of various mitigation strategies on CH_4 emission from rice paddies on a regional or national scale, computation models including variations in climate, soil, and field management, are often used. In this study, autumn shallow tillage, an appealing option with little additional cost, was evaluated with DNDC-Rice, which is a comprehensive process-based biogeochemistry model. A hypothesis is proposed in Chapter III: namely that using shallow tillage in autumn reduces CH_4 emissions only in fields where excess soil water retards the aerobic decomposition of straw during the fallow season. This hypothesis was validated with the DNDC-Rice model. Before the evaluation of autumn shallow tillage as a CH_4 mitigation option, the accuracy of the estimation of CH_4 emission by DNDC-Rice model was confirmed with observed data from six experimental fields where autumn tillage was performed at conventional depth (15 cm). A virtual condition was fed to the model to increase soil water contents from an experimental field (Morioka, Iwate prefecture in Japan) and the effects of autumn tillage depth on cumulative CH_4 emissions during the rice growth season were compared with different soil water regimes in the fallow season. As a result, there was no effect of autumn tillage depth on cumulative CH_4 emission during the next rice growth season even with high soil water content condition during fallow season. However, a trial with a minor revision of the DNDC-Rice model showed the possibility of model improvement to describe the effects of change in autumn tillage

depth on cumulative CH_4 emission in the next rice growth season with DNDC-Rice model evaluation.

4.2 INTRODUCTION

Global CH_4 emissions from rice paddies are estimated to account for 33 to 40 Tg yr-1 (IPCC, 2013). These values are estimated by both 'top-down' estimation, based on global atmospheric measurements of CH_4 concentration, and 'bottom-up' estimations as the result of regional or national estimations. Generally, bottom-up estimations have high compatibility with each region and country and adequately describe the features of emission patterns. In the upscaling of field emissions to regional or national levels, high uncertainty remains because of large fluctuations in CH_4 emission rates as affected by soil, climate, and the farming management of paddy fields (Schütz et al., 1989a; Inubushi et al., 1990; Yagi and Minami, 1990; Sass et al., 1991; Wassmann et al., 2000a; Itoh et al., 2011). Schütz et al. (1989a) showed the seasonal and daily fluctuation of CH_4 was related to soil temperature, farming managements such as fertilizer amendment, and the addition of straw. Yagi and Minami (1990) measured CH_4 emissions from four different types of paddy soils with several farming management systems and discovered differences in CH_4 emission among soil types, farming management processes such as the amendment of mineral fertilizer, and the application of straw and field drainage. Wassmann et al. (2000a) compared CH_4 emission among 8 measuring stations in 5 Asian countries and concluded that local variations in crop management affect more than climate and soil with regards to the amount of CH_4 emission. For a more accurate global estimation, better regional and national scale estimations including soil, climate and management differences are necessary. To estimate the CH_4 emission on a regional or national scale, various estimation models for CH_4 emission have been developed. Wania et al. (2010) incorporated a model for simulation of CH_4 emission from peatlands into the Lund-Potsdam-Jena (LPJ) Dynamic Global Model and named that the LPJ- Wetland Hydrology and Methane (WHyMe). Spahni et al. (2011) simulated global net CH_4 emissions from peatland, wetland, and rice paddies using LPJ-WHyMe.

One of the most advanced estimation models is the DNDC (DeNitrification DeComposition) - Rice model (Fumoto et al., 2008, 2010) developed by modifying DNDC, a comprehensive process-based model developed to simulate carbon and nitrogen cycles and gas (N_2O, N_2, NO, NH_4, CO_2, and CH_4) emissions in upland fields (Li et al., 1992). The DNDC model was revised to be applicable to anaerobic biogeochemistry by Li et al. (2004), and further refined to simulate gas emissions from paddy fields by Pathak et al. (2005) and Babu et al. (2006) for Indian rice agriculture. Fumoto et al. (2008, 2010) made major revisions to make DNDC more appropriate for estimating CH_4 emissions from paddy fields and named it DNDC-Rice. Though DNDC-Rice has only been recently developed, it has been applied and validated in various regions with different field conditions (Smakgahn et al., 2009; Katayanagi et al., 2012; Fumoto et al., 2013; Minamikawa et al., 2014). In 2013, Hayano et al. simulated national-scale CH_4 emissions for Japan, combining the DNDC-Rice model and GIS database, as a tier 3 inventory for Japan according to the IPCC guidelines. The field scale CH_4 mitigation potential of prolonged midseason drainage was assessed by the DNDC-Rice model (Minamikawa et al., 2014). With the combination of these studies, it is also possible to evaluate the effect of a certain mitigation strategy on a national scale.

However, there is no previous research evaluating the effect of autumn shallow tillage on CH_4 mitigation using the DNDC-Rice model. To evaluate the effect of using shallow tillage in autumn on CH_4 emission on a regional or national scale, the application of a simulation model such as DNDC-Rice is very important.

In addition, since DNDC-Rice is a comprehensive process-based model, it would be effective to use this model to explore the CH_4 mitigation mechanisms of autumn shallow tillage through changing the input parameters appropriately.

As the purpose of this study, the first aim is to express the degree and applicable range of CH_4 mitigation effect with the use of shallow autumn tillage. The second is to explore the mechanism of CH_4 mitigation using shallow autumn tillage through this study.

4.3 METHODS

4.3.1 Model description

The DNDC-Rice model consists of three major submodels: soil climate, crop growth, and soil biogeochemistry. A schematic view of the DNDC-Rice model is described in Figure IV-1. Daily weather conditions, soil properties, and farming management are required as inputs.

In the soil climate submodel, a soil moisture characteristic curve is determined for each soil texture according to the following equations advocated by Clapp and Hornberger (1978):

$$\psi = \Psi_s W^{-b} \qquad \text{for } (W < W_i) \qquad (1)$$

$$\psi = -\mathrm{m}(W-n)(W-1) \qquad \text{for } (Wi \leq W \leq 1) \qquad (2)$$

Wi is the soil relative wetness on an inflection point, where the differential of the moisture characteristic curve changes to a decreasing from an increasing function. In eq. (1), W is the soil relative wetness equal to the ratio of the current volumetric water content to a saturated volumetric water content (θ/θ_s), ψ_s is the matric potential of a saturated condition, and b is an empirical coefficient. For eq. (2), the parameters m and n are calculated as

$$\mathrm{m} = \frac{\psi_i}{(1-W_i)^2} - \frac{\psi_i b}{W_i(1-W_i)} \qquad (3)$$

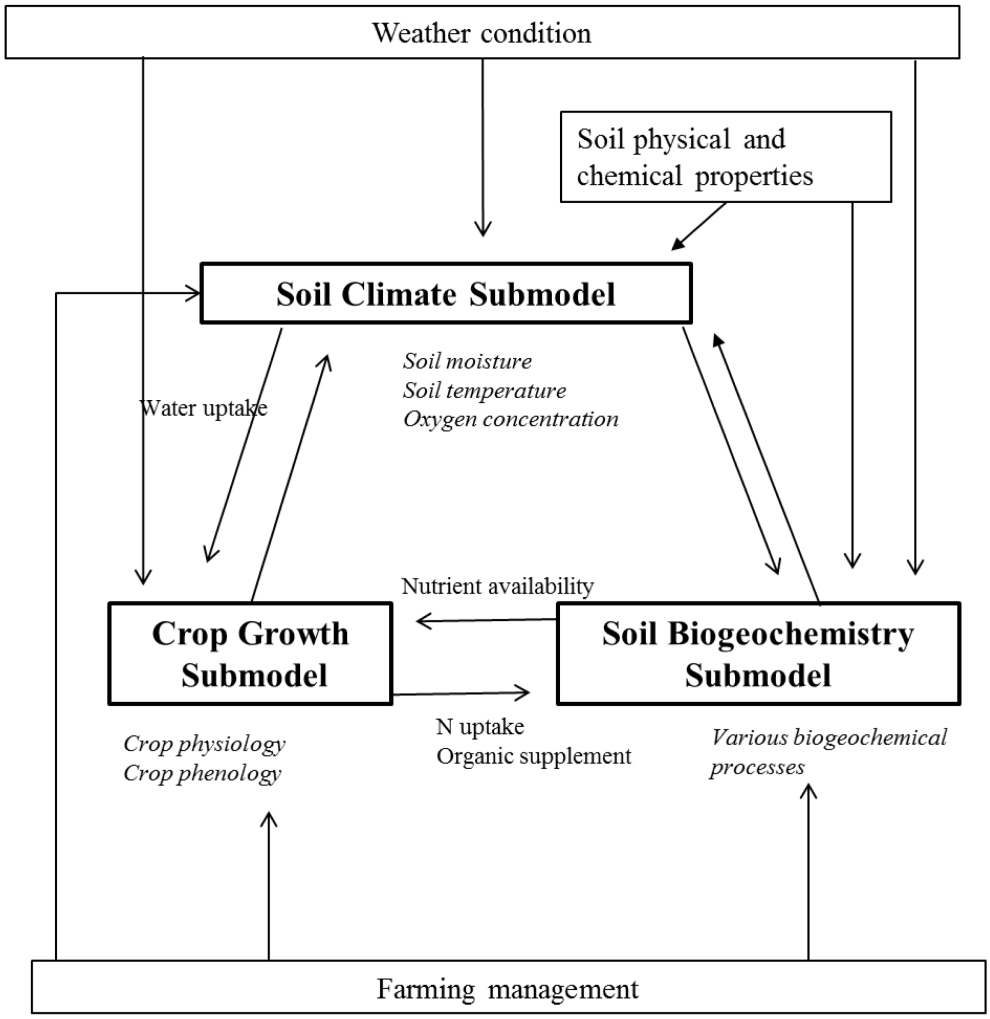


Fig. IV-1. Schematic view of DNDC-Rice model

$$\text{n} = 2\text{W}_i - \left(\frac{\psi_i b}{mW_i}\right) - 1 \qquad (4)$$

The coefficients used in above equations are determined for each soil texture in the DNDC-Rice model. One-dimensional water flow rate in soil is decided from equations (1)-(4). Soil temperature, oxygen concentration in soil, soil carbon content and ion concentrations in soil are also calculated in the soil climate submodel referring to weather conditions, farming management and soil water flows. When the field is covered with flooding water, the daily mean temperature of the flooding water is calculated with the micrometeorological model of Kuwagata & Hamasaki (2000) for the accurate estimation of heat transport in soil. A total of 50 cm of soil profile is divided horizontally into layers of same thickness and all calculations are performed for each layer in descending order (Fumoto *et al.*, 2008). Diffusion effects on the transport of water, heat and nutrients between soil layers are also taken into account.

Crop growth and the accompanying transport of water, gases and nutrients are simulated in the crop growth submodel. The MACROS model (Penning de Vries *et al.*, 1989) and ORYZA1 rice model (Kropff *et al.*, 1994) is integrated to the DNDC-Rice model for an accurate description of photosynthesis, respiration, and Carbon allocation in crops (Fumoto *et al.*, 2008). Two types of crop growth submodel are available according to the needs of the users: empirical and physiology/phenology. Specific parameters for each crop such as an initial biomass, crop development rates and a maximum rate of photosynthesis are predetermined for 40 types of crop in the empirical submodel, whereas users can input them manually when using the physiology/phenology submodel. A function named the Development Stage (DS) which is defined as 0.3, 1.0, 2.0 for the transplanting, heading, and maturation stages, respectively, is used to estimate the allocation of assimilated carbon, plant height, leaf area, the loss rate of leaves and roots, the tiller number with the heat unit model (Shimono, 2003) and the gas conductance of a tiller during crop growth.

The soil biogeochemistry submodel includes many reactions related to the activities of soil microorganisms such as the decomposition of organic carbon, denitrification, nitrification, the reduction of oxides and CH_4 production. The decomposition rates of soil organic matter pools are calculated with first-order reaction kinetics which include the affecting factors of soil temperature, soil moisture, N deficiency, the oxygen concentration in soil, clay content and the tillage performance:

$$\frac{\mathrm{d}[C]}{dt} = -SDR[C]\, f_T\, f_M\, f_N\, f_{O_2}\, f_{clay}\, f_{tillage}\, DRF \qquad (5)$$

where [C] is organic C pools of residues, microbial biomass or humads (kgC ha^{-1}), SDR is specific decomposition rate (day^{-1}), f_T, f_M, f_N, f_{O2}, f_{clay}, and $f_{tillage}$ are factors related to soil temperature; soil moisture, N deficiency, the oxygen concentration in soil, clay contents and tillage performance. DRF is a reduction factor of carbon decomposition due to the field conditions (Fumoto *et al*., 2008).

Denitrification, nitrification, reduction of oxides, CH_4 production, and CH_4 oxidation are calculated using Michaelis-Menten kinetics. For example, CH_4 oxidation reaction is expressed as:

$$\mathrm{OXD}_{CH_4} = v_{max} \times \frac{[CH_4]}{K_{CH_4\_CH_4OXD+[CH_4]}} \times \frac{[O_2]}{K_{O_2\_CH_4OXD} + [O_2]} \times \mathrm{Q}_{10}{}^{\frac{T-RefT}{10}} \quad (6)$$

where OXD_{CH4} is the rate of CH_4 oxidation (mol m^{-3} h^{-1}), v_{max} is the maximum CH_4 oxidation rate, and K_{CH4_CH4OXD} and K_{O2_CH4OXD} are constants of Michaelis-Menten kinetics on CH_4 oxidation for CH_4 (mol_{CH4} m^{-3}water) and O_2 (mol_{O2} m^{-3}water), respectively. T is the soil temperature and Ref T is a reference temperature (25 °C).

These three submodels feed their results back to each other. Crop growth affects water and nutrient uptake by plants, and the amount of supplemental carbon to soil from root exudates or dead cells. Microbial activities change both nutrient efficiency in plants and the oxygen concentration of soil.

4.3.2 Model Validation

To confirm the validity of using the DNDC-Rice model in this study, annual CH_4 emissions under various climate, soil and management conditions during the experimental years were calculated. Measured data from six experimental fields in different prefectures in Japan; Sapporo (*S*), Iwate (*I*), Yamagata (*Y*), Fukushima

(*F*), Niigata (*N*), and Aichi (*A*), were used for the validation of the DNDC-Rice model in this study. Autumn tillage for each site was performed at 15 cm depth. The locations and experimental periods for each field are illustrated in Figure IV-2. Soil properties, field management, crop yield, and CH_4 flux in rice growing season were measured as input data for the model simulation. For weather data at each experimental site, data from the nearest area covered by the Automated Meteorological Data Acquisition System (AMeDAS) by the Japan Meteorological Agency, were collected respectively for each field. Microbial activity was set to 0.1 in Andisol sites (*S* and *I*) and to 1.0 in the other sites according to previous research (Minamikawa *et al*., 2014).

Two types of input parameter were treated as fitting parameters: the groundwater level in experimental fields and the Fe^{3+} concentration in soil. Accurate data for groundwater levels were missed in some experimental sites. Therefore, only the gross information ("high" or "low") was used to set the initial value of groundwater level. As an initial value of groundwater level, 50 cm and 99 cm (below the soil surface) are set for fields with "high" and "low" groundwater respectively to emulate conditions much higher and lower than the 70 cm depth suitable for crop growth and the use of machinery (Hayano *et al*., 2013). Fe^{3+} concentration represents the number of major electron acceptors in the soil and has a large effect on the amount of CH_4 emission (Fumoto *et al*., 2008). Although Fe^{3+} concentration in the soil of each experimental field was

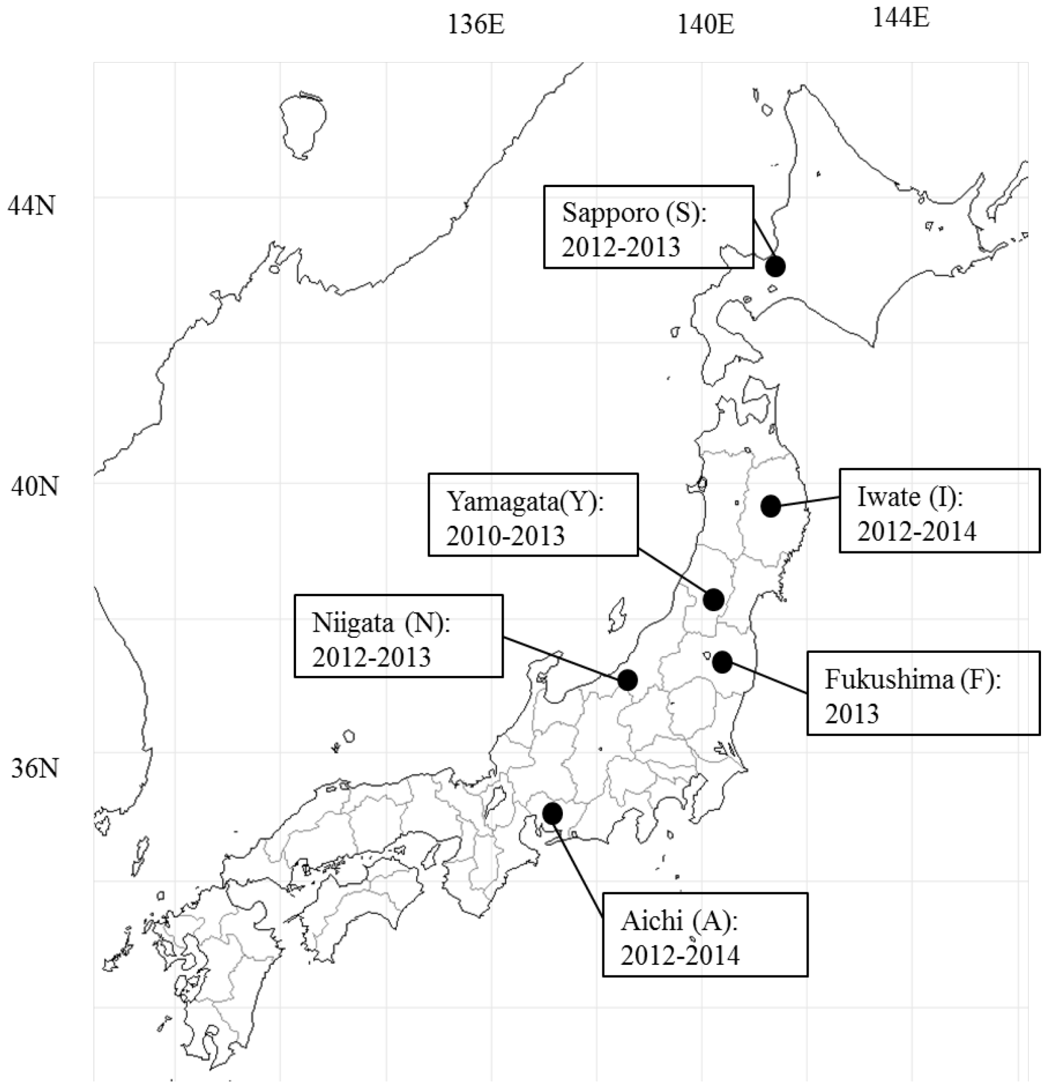


Fig. IV-2. Location and test years of the field sites used for validation of DNDC-Rice model measured, other electron acceptors found in soil such as Mn^{4+} were not measured in this study. To take into account the influence of other electron acceptors, Fe^{3+} concentration was treated as a fitting parameter. The initial value of Fe^{3+} concentration was set at 0.09 mol kg^{-1}soil, the default value for the DNDC-Rice model at each experimental site except for *I* and *N,* which have a much larger measured value of Fe^{3+} (> 0.09). The measured soil Fe^{3+} concentrations (0.40 and 0.28 mol kg^{-1}soil for *I* and *N*, respectively) were used as the initial values in these two experimental sites, respectively. The two parameters were set to fit the beginning (1st) day of CH_4 emission after field flooding, with regards to measured data and model simulation.

To stabilize the simulation results, a preliminary run for 20 years with constant input was performed before each calculation (Fumoto *et al.*, 2008). Farming management parameters (including crop yield) of the first experimental year of each field were used for the preliminary run. Because the effect of autumn field conditions on CH_4 emissions in the next growing season was the focus of this study, weather data from the year preceding the beginning of the experiment was used for the preliminary run.

4.3.3 Simulation with virtual condition in Iwate

In chapter III, a hypothesis about the mitigation effect of shallow tillage in autumn was proposed: shallow autumn tillage should be an effective mitigation option only in a field where the straw decomposition in the fallow season would be retarded by excess water in the soil. To assess this hypothesis, simulation by DNDC-Rice was conducted using virtual soil conditions of increased soil water content in the fallow season of the Iwate experimental site. Three types of soil conditions were changed to increase the soil water content in the fallow season: soil texture, groundwater level and bulk density. All other parameters were similar to those shown in Table IV-1. After the selection of handling inputs for the virtual conditions of increased soil water content, CH_4 emissions of conventional (15 cm) and shallow (7 cm) autumn tillage were compared. Parameters decided during the validation process (Table IV-1) were used for each simulation as input except for the handling one. The preliminary run was performed with the same validation process.

4.4 RESULTS

4.4.1 Model Validation

Some of the input parameters after fitting are shown in Table IV-1. Soil textures in experimental sites are shown according to soil classification systems from the United States Department of Agriculture (USDA), and vary from loam to sandy clay. After adjustment to fit both measured and simulated first day of CH_4 emission to the model, Fe^{3+} concentration and groundwater levels as fitting parameters became 0.09, 0.38, 0.13, 0.09, 0.28, 0.09 mol kg^{-1}soil and 99, 99, 99, 99, 50, 56, 50 cm for the *S*, *I*, *Y*, *F*, *N*, and *A* experimental sites, respectively. Groundwater level was not changed from the initial value except for at the *N* site, in which the measured emission was much lower than the simulated one even after adjustment to the Fe^{3+} concentration. The measurement and simulation results during one year for each experimental site are shown in Figure IV-3. The first day of CH_4 emission for the model simulations were generally matched to measured data, except for the Andisol sites (*S* and *I*); for these sites the simulated first days were later than those measured even after the decline of microbial activity was taken into account.

Figure IV-4 shows the relationships between simulated and measured CH_4 emission in the rice growing season. The simulation of cumulative CH_4 emission with the DNDC-Rice model after parameter fitting was well matched with that measured (liner regression, $R^2 = 0.94$, $p < 0.001$).

Table IV-1 Major input parameters of each experimental fields after fitting for measured CH_4 emission

	Sapporo	Iwate	Yamagata	Fukushima	Niigata	Aichi
Latitude and Longtitude	43°00'N, 141°24E	39°42'N, 141°09E	38°14'N, 140°14E	37°28'N, 140°23E	37°07'N, 138°16E	35°10'N, 137°04E
Experimental period	2012-2013	2012-2014	2010-2013	2013	2012-2013	2012-2014
Soil texture *1	loam	loam	clay loam	sandy clay loam	clay loam	sandy clay
bulk density ($g\ cm^{-3}$)	1.03	0.6	1.2	0.9	0.9	0.97
Fe^{3+} (mol kgsoil^{-1})	*0.09*	*0.38*	*0.13*	*0.09*	*0.28*	*0.09*
pH(H_2O)	6.0	6.7	6.0	6.0	5.5	5.7
Microbial activity	0.1	0.1	1.0	1.0	1.0	1.0
N fertilazation (kg N ha^{-1})	75	90	60+20	40	47+15+15	48
Straw application (kg ha^{-1}) *2	1883	2578	2744	2400	2364	2573
Yield (kg ha^{-1}) *2	6875	6275	5561	5664	6276	5465
depth of ground water (cm)	*99*	*99*	*99*	*50*	*56*	*50*

*1 Soil classification of USDA
*2 Average value of experimental periods
Italized values are decided as fitting parameter

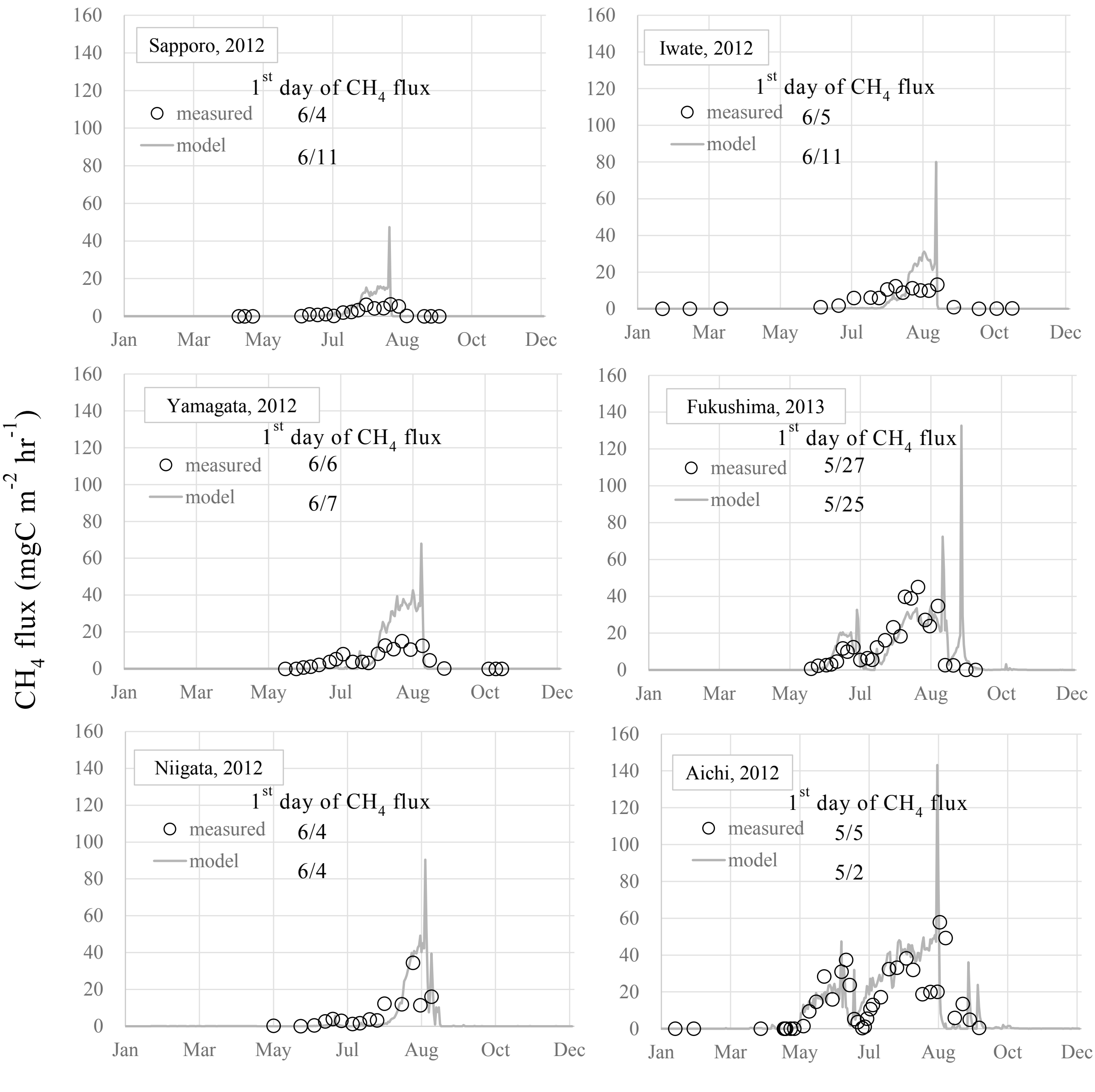


Fig.IV-3. Annual changes in CH_4 flux at 6 experimental fields in Japan: comparison of measured results and those calculated by DNDC-Rice model with parameter fitting. Parameter fitting was performed to match the 1st day of measured and simulated CH_4 flux.

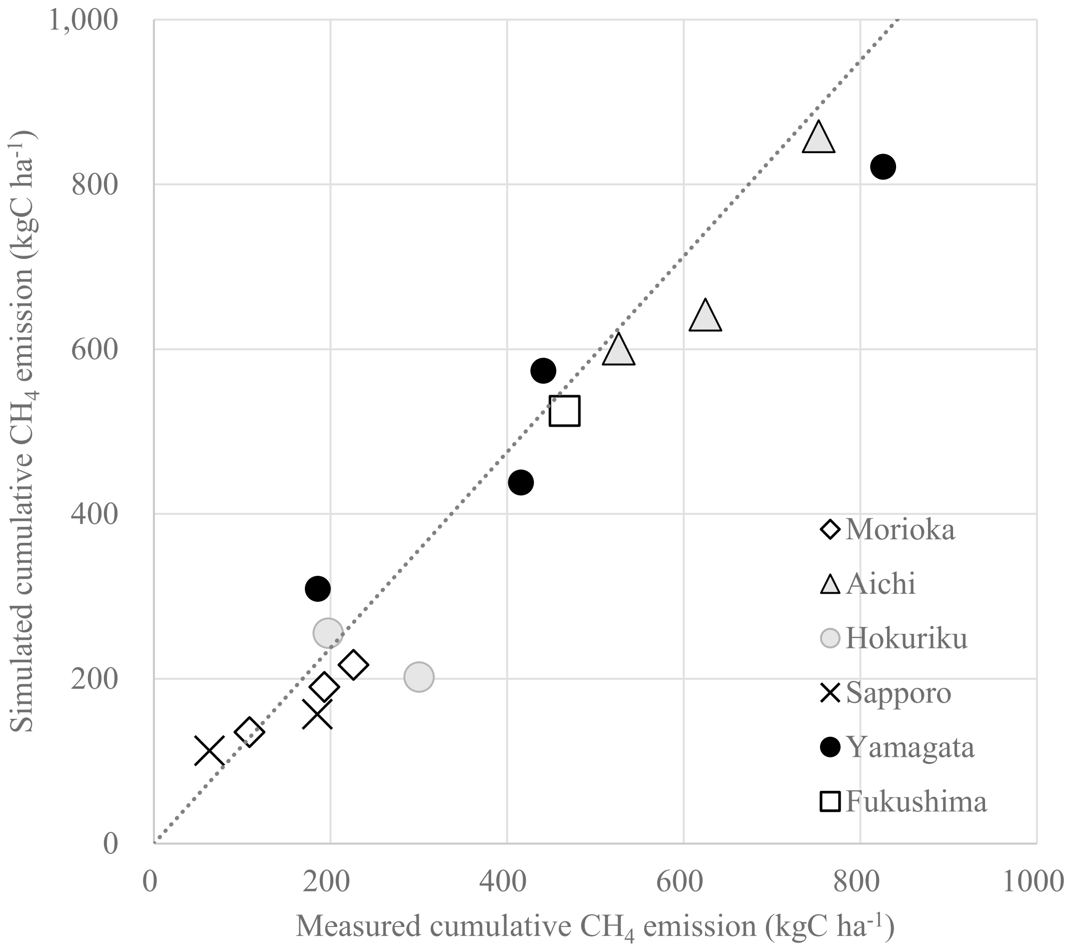


Fig.IV-4. Relationships between measured and simulated cumulative CH_4 emission. Data from six experimental fields during several test years are used. Each field was tilled with conventional (15 cm) depth just before the fallow season.

4.4.2 Simulation with virtual condition in Iwate field

Sensitivities of soil water content with changed parameters in the Iwate experimental field are shown in Figure IV-5. Changes to soil texture (Fig. IV-5a) alter the water content of soil more than the other two parameters (Figs. IV-5b and IV-5c). Based on the above results, soil texture was selected as the handling item to set virtual conditions for the Iwate experimental field. Two sets with different soil textures, loam and clay (as classified by the USDA), were prepared to express the conditions of soil water content in the fallow season, low and high, respectively. CH_4 emissions from paddy fields were simulated using these data sets and different depths of autumn tillage, both conventional and shallow.

Simulated cumulative CH_4 emission is shown in Figure IV-6. Simulated cumulative CH_4 emission for soils with a loam texture varied from 135 to 217 kg C ha^{-1} with conventional tillage, and from 144 to 224 kg C ha^{-1} with shallow tillage (Fig. IV-6a). Simulated cumulative CH_4 emission for soils with a clay texture were higher, ranging from 371 to 512 kg C ha^{-1} with conventional tillage and 394 to 571 kg C ha^{-1} with shallow tillage (Fig. IV-6b). Two-way ANOVA results showed that simulated cumulative CH_4 emissions were significantly affected by year ($p > 0.01$ and $p > 0.05$ for loam and clay soil conditions, respectively) but not by tillage practice ($p = 0.10$ and $p = 0.16$ for loam and clay conditions, respectively) in both soil texture conditions.

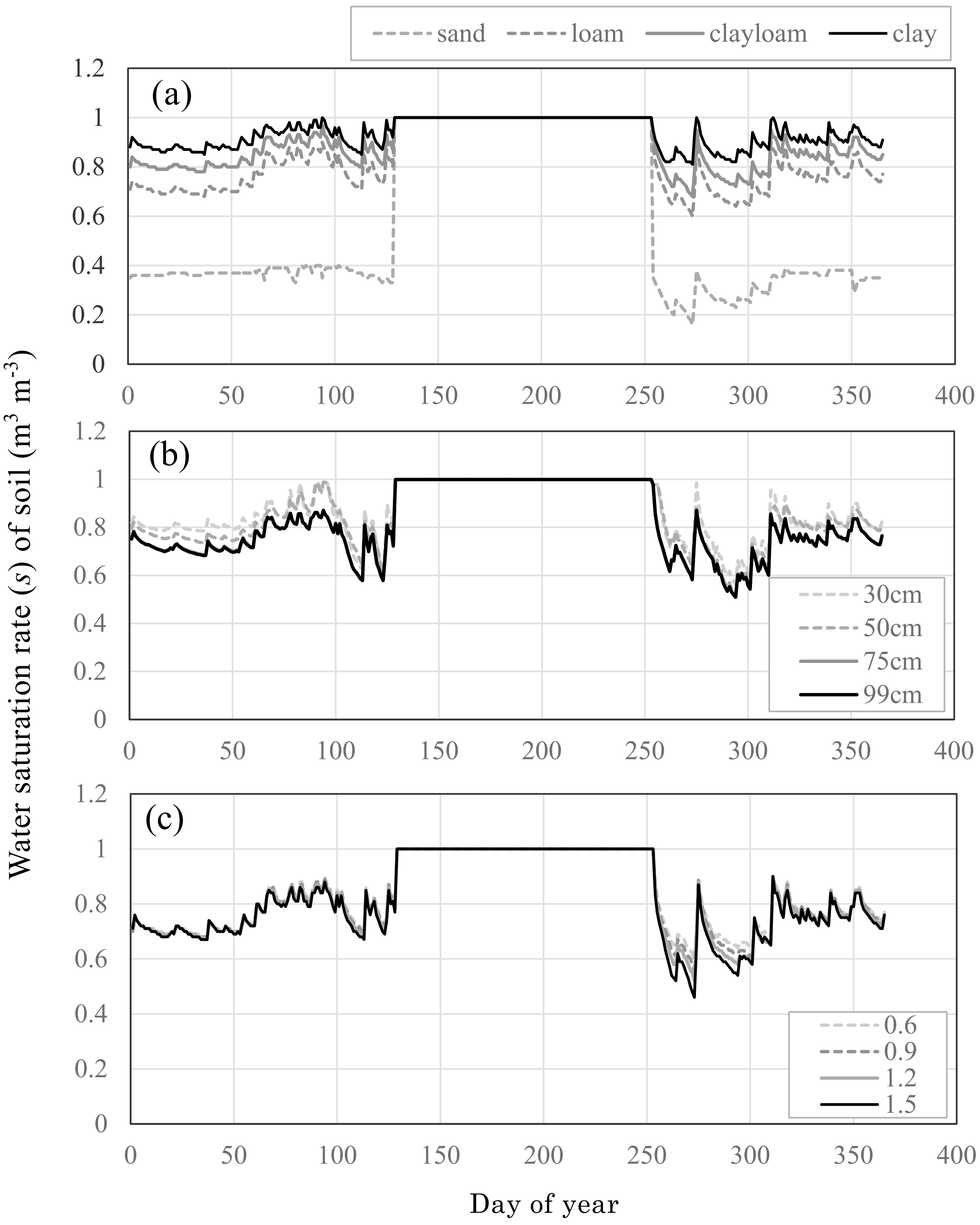


Fig. IV-5. Changes in soil water saturation rate (S) corresponding with the change in (a) soil texture, (b) groundwater level, and (c) bulk density of soil.

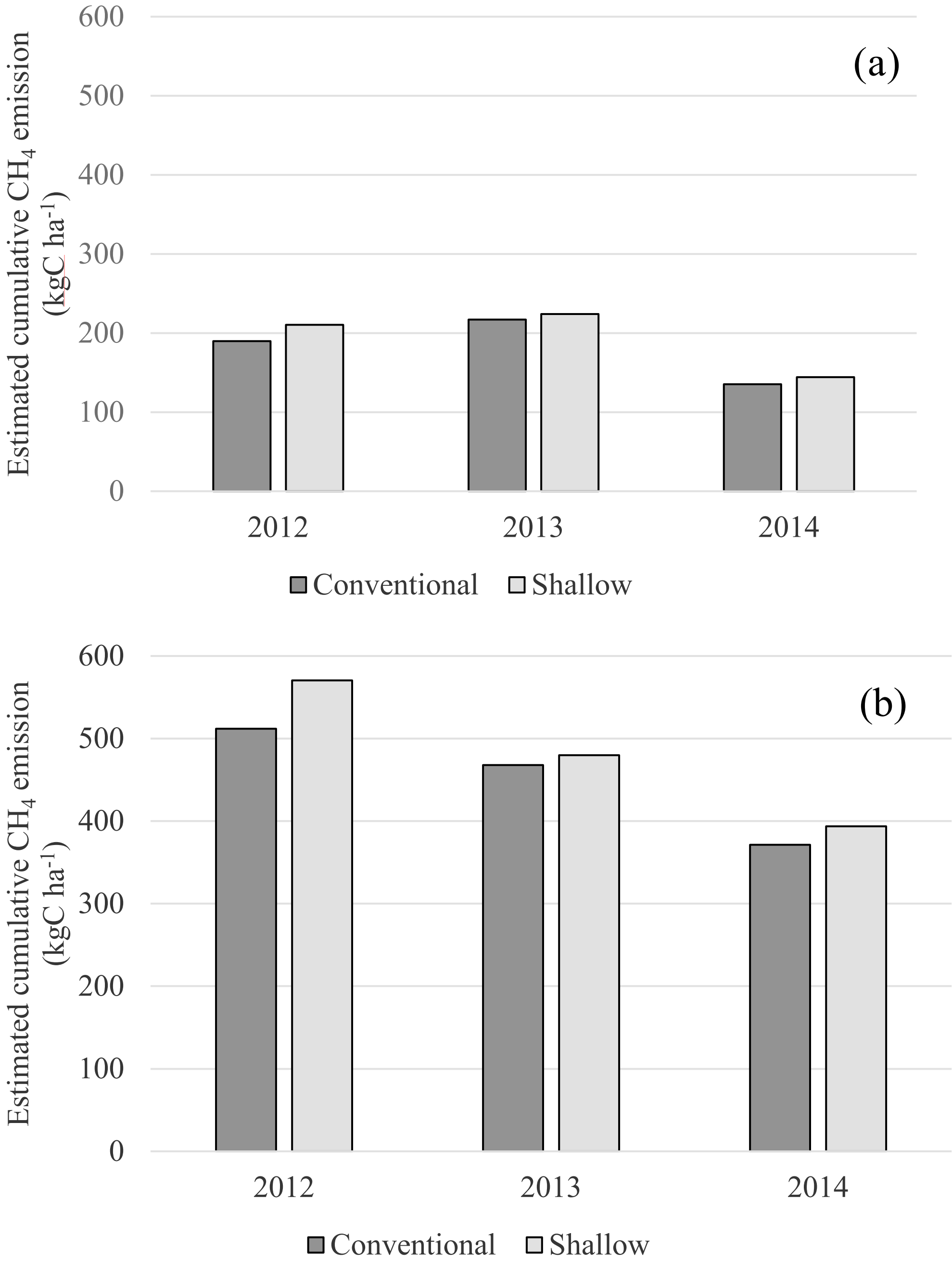


Fig. IV-6. Cumulative CH_4 emission during the rice growth season from the Morioka experimental field with the virtual conditions of (a) loam and (b) clay soil textures as estimated with the current DNDC-Rice model.

4.5 DISCUSSIONS

4.5.1 Model Validation

After parameter fitting to match the start time for CH_4 emission, simulations for CH_4 flux and cumulative CH_4 emission from six experimental paddy fields were performed by the DNDC-Rice model (Fig. IV-4). Soil Fe^{3+} concentration and groundwater level were adjusted as fitting parameters in this study. In general, increased Fe^{3+} concentration retards the start time of CH_4 flux and decreases CH_4 emission, especially in the early rice growth season for the DNDC-Rice model, because of oxygen competition between Fe-reduction bacteria and methanogen. Groundwater level also retards start time of CH_4 emission and decreases CH_4 emission; however, this is not only in the early period but for the entire rice growing season. In the Andisol sites (*S* and *I*), the simulated start of CH_4 flux after parameter fitting is delayed even more than that measured, even after the decline of microbial activity in Andisol has been taken into account (Fig. IV-3). The reason for this gap could be additional characteristics of Andisol, such as high permeability to water or a large amorphous proportion of clay minerals. However, more details cannot be discussed within the results of this study. With the high correlation between measured and simulated cumulative CH_4 emission (Fig. IV-4), it can be concluded that the DNDC-Rice model with the fitted parameters could be applied to express cumulative CH_4 emissions in this study.

4.5.2 Simulation with virtual condition in Iwate field

To set a virtual condition with a high soil water content for the fallow season, the sensitivity of soil water content with a change of 3 different input parameters related to water flow in soil was compared. As shown in Figure IV-5, soil texture has a large effect on soil water content compared to groundwater level and soil bulk density. For the DNDC- Rice model, several physical soil parameters such as clay content, field capacity and the wilting point of soil are decided together with the soil texture automatically. Although model users can input these parameters manually with regards to their needs, the default values were used in this study and this might be the reason for the drastic changes in soil water regime with changes to the soil texture input.

Using loam and clay as the 2 soil texture conditions, cumulative CH_4 emissions were simulated with different depths of autumn tillage, conventional and shallow. Loam and clay conditions represent a 'high' and a 'low' soil water content in the fallow season, respectively. Higher CH_4 emissions in clay conditions might be explained by the following: low aerobic decomposition rates of organic matter due to a higher soil water regime during the fallow season, low contents of alternative electron acceptors such as Fe^{3+} because of insufficient soil oxidation during the fallow season, or an early drop in soil Eh to the lower value at which methanogenesis could occur.

According to the hypothesis proposed in Chapter III, autumn shallow tillage should show a mitigation effect in fields where excess soil water in the fallow season retards the aerobic decomposition of incorporated rice straws, even if there are none of these effects in fields with high water percolation rates and thus successfully aerobic conditions for the fallow fields. However, there was no effects due to the depth of autumn tillage to cumulative CH_4 emission in the following rice growth season even in clay conditions in which the soil water content in autumn is high (Fig. IV-6). These results imply two possibilities. Firstly, the mechanism for a mitigation effect of autumn shallow tillage is not related to the water regime in the fallow season. If the decline of CH_4 emission with shallow tillage before the previous fallow season is not due to the alleviation of excess water in the straw-incorporated layer, the effect cannot be simulated even under conditions of waterlogging. Further studies measuring accurate soil temperature, moisture and microbial activities during the fallow season are required to track this possibility. Another possibility is the model problem. If the current DNDC-Rice cannot simulate the tillage effect on aerobic decomposition rates, it cannot simulate the effect of shallow tillage in autumn on CH_4 emission in the following rice growth season. In the current model, tillage practice leads to the redistribution of water and nutrients in soil, the addition of stubbles from the soil surface into soil carbon pools, a temporary increase of oxygen concentrations in soil, and an end to soil cracking. Among these tillage effects, the increase of soil oxygen concentration should affect the aerobic decomposition rate of incorporated rice straws.

4.5.3 Trial minor revision of DNDC-Rice

To assess the second possibility mentioned above, minor revisions were made to the current DNDC-Rice model. In the current model, the decomposition rate of soil organic pools is expressed in eq. (5) as mentioned above.

$$\frac{\mathrm{d}[C]}{dt} = -SDR[C]\, f_T\, f_M\, f_N\, f_{O_2}\, f_{clay}\, f_{tillage}\, DRF \qquad (5)$$

In eq. (5), $f_{tillage}$ is a factor of tillage performance. After tillage, the gas fraction in the tilled layer will increase temporarily without eliminating any liquid or solid phase (a virtual increase). The increase range is 0.1 of the volumetric ratio on the day of tillage and it decreases linearly with the rate of 0.001 day^{-1}. f_M is the reduction factor for soil moisture. In the current model, aerobic decomposition of organic matter in the soil with very low soil water content is limited as in the following equation using the water filled pore space as a unit (WFPS) rate (m^3 m^{-3}):

$$\mathrm{RFMM1} = \frac{\mathrm{day\_WFPS[l]} - 0.1}{Fldcap - 0.1} \qquad (7)$$

where RFMM1 is a reduction factor due to the deficiency of soil moisture, day_WFPS[l] is a daily average of WFPS in a specific soil layer, *Fldcap* is a

WFPS value for field capacity (>0.5). If day_WFPS[l] is lower than 0.1, RFMM becomes 0 and no decomposition of organic matter will occur. When the day_WFPS[l] is greater than the *Fldcap*, there is no limitation on decomposition of organic matter due to soil moisture shortage. Additionally, the reduction of organic decomposition by excess water in the soil is expressed as a function of available oxygen content in the current model. The rate of aerobic decomposition as compared to total decomposition (aerobic + anaerobic) is estimated as:

$$aero\_f = O_2[l] \times \frac{K\_O_2 + 1.0}{K\_O_2 \times \max\_O_2[l] + O_2[l]} \qquad (8)$$

where *aero_f* is the rate of aerobic decomposition as compared to total decomposition, O_2 [l] is O_2 content in a specific soil layer (kg O_2 ha^{-1}), max_O_2 is the maximum O_2 content in that layer and K_O_2 is the Michaelis constant for O_2 saturation (0.1). Excess water in the soil layer inhibits gas exchanges between pedosphere and atmosphere and thus decreases the O_2 content in the soil layer earlier. A reduction factor for excess water in soil, RFMM2, is expressed with *aero_f* as follow:

$$\mathrm{RFMM2} = aero\_f + (1.0 - aero\_f) \times 0.2 \qquad (9)$$

Eq. (9) is based on the assumption that aerobic decomposition progresses 5 times more rapidly than anaerobic decomposition. And as clearly shown by the above equations, the inhibition of aerobic decomposition by soil excess water is only expressed as a function of the available oxygen content in soil in the current model (Fumoto *et al*., 2008).

To heighten the effect of excess water on the aerobic decomposition rate, a minor revision was added to the current DNDC-Rice model. An additional limitation on organic matter decomposition by excess water was defined as follow:

$$\mathrm{RFMM2'} = 1.0 - 0.3 \times \frac{(\mathrm{day\_WFPS[l]} - 0.8)}{1.0 - 0.8} \qquad (10)$$

With the revised version, RFMM2’ will be multiplied to RFMM2 and the decomposition rates of organic matter are severely reduced when day_WFPS[l] is higher than 0.8 (m^3 m^{-3}).

The simulation of CH_4 emission for the two soil textures (loam and clay) and the two depths of autumn tillage (conventional: 15 cm and shallow: 7 cm) was performed with the revised model in the same manner as with the current DNDC-Rice model. Figure IV-7 shows the simulated cumulative CH_4 emission for the revised model. Simulated cumulative CH_4 emission with loam texture conditions varies between 142 and 209 kg C ha^{-1} with conventional tillage, and 146 to 212 kg C ha^{-1} with shallow tillage. With clay texture conditions, the simulated cumulative CH_4 emission ranged from 644 to 744 kg C ha^{-1} and from 632 to 721 kg C ha^{-1} with conventional and shallow tillage, respectively. Using the revised model, autumn shallow tillage showed a trend to reduce the cumulative CH_4

emission in the following rice growth period only under clay texture conditions even though there was no significance found using two-way ANOVA (p = 0.1825 and 0.061 in loam and clay texture conditions, respectively). This trend is clearer with comparison of the cumulative CH_4 emission in 60 DAT (Fig. IV-8). By the current model, the cumulative CH_4 emissions for 60 DAT with conventional and shallow tillage practice were estimated to be 2.5 to 6.0 kg C ha^{-1} and 2.6 to 6.7 kg C ha^{-1} from the loam field, and 37.5 to 108.1 kg C ha^{-1} and 45.8 to 113.0 kg C ha^{-1} from the clay field, respectively. There is no significance between the different tillage practices in two-way ANOVA for both of the different soil texture conditions (p = 0.1751 and 0.2034 in loam and clay texture conditions, respectively). On the other hand, the estimated cumulative CH_4 emissions for 60 DAT with conventional and shallow tillage practices using the revised model were 2.1 to 7.5 kg C ha^{-1} and 2.1 to 7.9 kg C ha^{-1} in the loam texture condition, and 155.4 to 289.2 kg C ha^{-1} and 142.7 to 268.6 kg C ha^{-1} in the clay texture condition, respectively. With the revised model, there is a significant decrease in cumulative CH_4 emission for 60 DAT with the shallow tillage practice compared with the conventional one only in the clay texture condition (p = 0.1552 and 0.0182 in loam and clay texture conditions, respectively). These results suggest that there is a possibility of underestimation in the current DNDC-Rice model for the inhibition of the organic decomposition process by excess water, and further research and revision on DNDC-Rice could make it possible to evaluate the CH_4

mitigation effect of autumn shallow tillage.

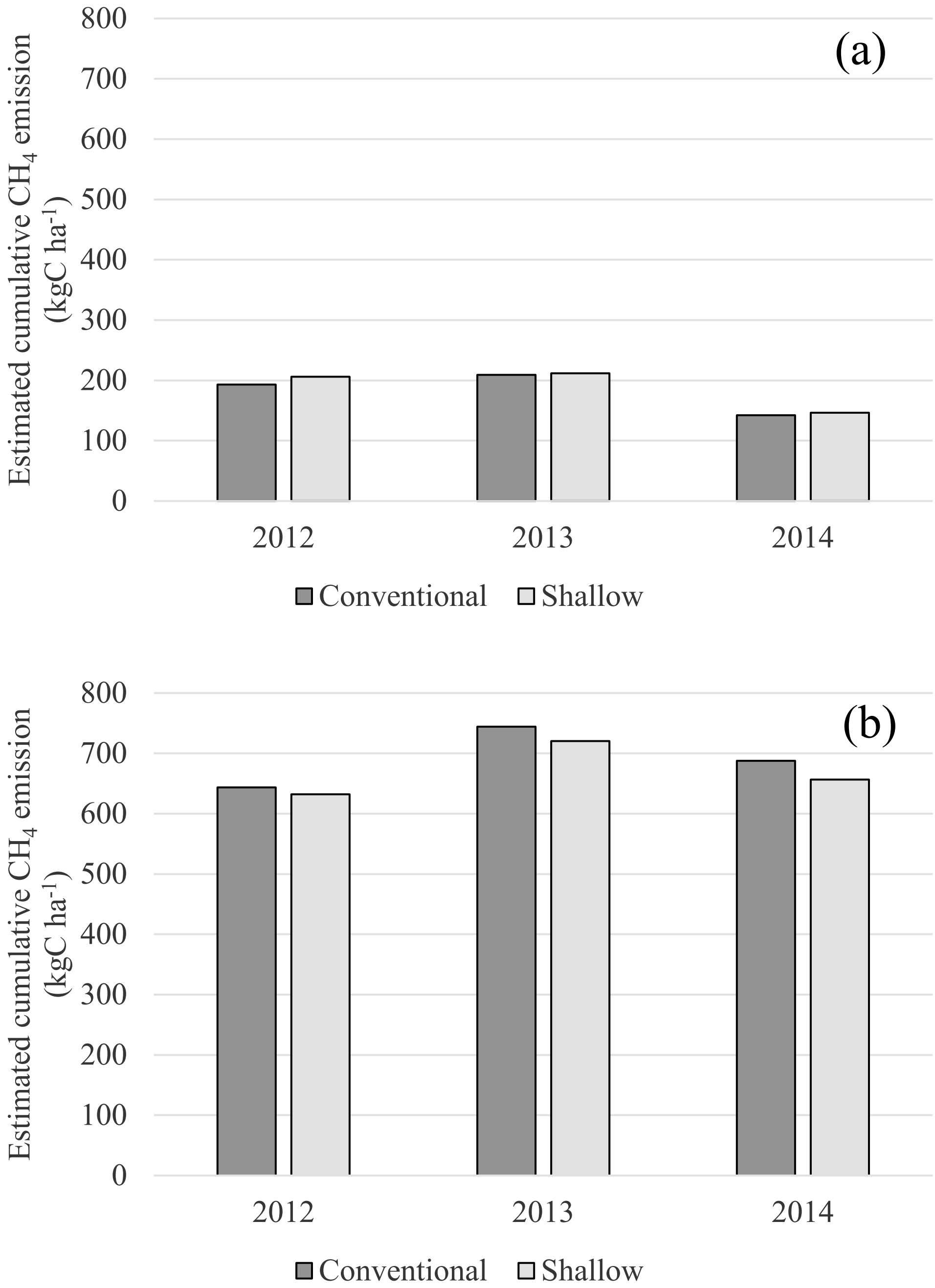


Fig.IV-7. Cumulative CH_4 emission during the rice growth season from the Morioka experimental field with the virtual conditions of (a) loam and (b) clay soil texture as estimated with the revised DNDC-Rice model.

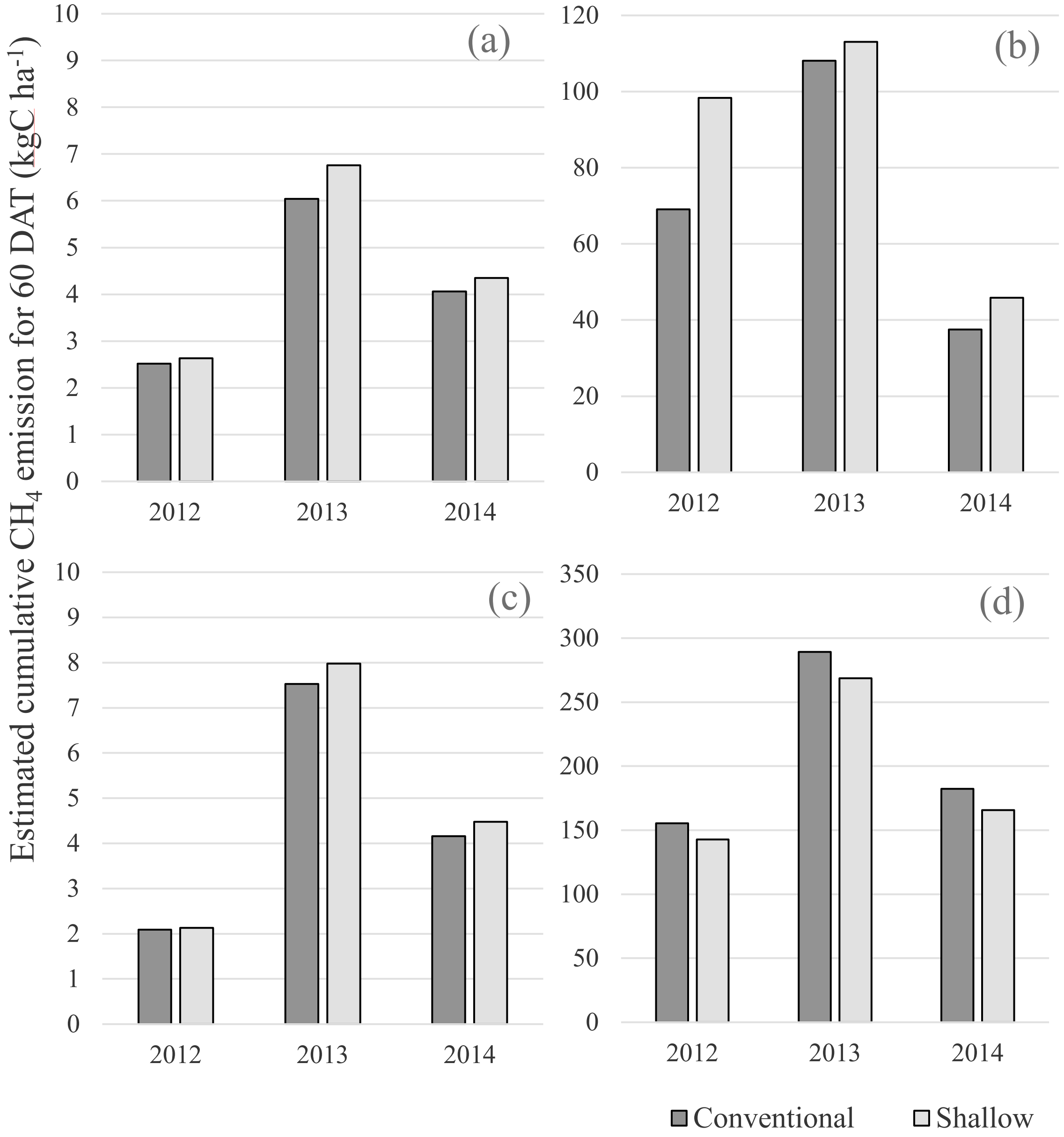


Fig. IV-8. Estimated cumulative CH_4 emission for 60 DAT with (a) the current model and Loam conditions, (b) the current model and Clay conditions, (c) the revised model and Loam conditions and (d) the revised model and Clay conditions.

4.6 CONCLUSIONS

To enable regional or national scale estimation, an evaluation of the use of shallow tillage in the autumn as a mitigation strategy for emitted CH_4 from paddy fields was performed using DNDC-Rice, a process-based biogeochemistry model. Model validation using observed data from 6 experimental fields in Japan confirmed that the DNDC-Rice model accurately describes the amounts of and fluctuation in cumulative CH_4 emission from paddy fields after the fitting of several parameters. Simulations using virtual conditions assuming that the soil water content would be high in the fallow season were carried out to assess a hypothesis made in Chapter III suggesting that shallow tillage in the autumn would only mitigate CH_4 emission in the following rice growth season in a field with high water content during the fallow season and in which rice straw was decomposed. Contrary to expectation, the effect of reducing the depth for autumn shallow tillage did not appear significant for either low or high water content in the fallow season. Two reasons could be formulated to explain this contradiction: a wrong hypothesis or an insufficiency in the current model. Trial minor revisions to the DNDC-Rice model showed the possibility of further revision to the model to describe the CH_4 mitigation mechanism of autumn shallow tillage. Further studies with accurate measurements of soil temperature, moisture, and microbial activities during the rice straw decomposition period in the field are needed to reveal more details on the mechanism and degree of CH_4 mitigation effect of autumn shallow tillage.

Chapter V:

General discussion

CH_4 emissions from paddy fields are a problem of global concern and practical mitigation strategies which can be applied by local farmers are a pressing need. In Japan, a-quarter of the total Japanese rice fields are located in the Tohoku region, in a cold and temperate climate. Since the development of agricultural machinery and chemical fertilizers, rice straw as a by-product of after-grain harvest tends to be left on the field, and is not added to composted material. Many previous researchers pointed out the risk of the direct incorporation of rice straw into soils in drastically increasing the CH_4 emission from rice paddy fields (Yagi and Minami, 1990; Wassmann *et al*., 2000b). In the Tohoku region, the risk of direct incorporation could be larger because low temperatures might retard the aerobic decomposition of the incorporated rice straw and thus increase the amount of substrate for methanogenesis during the next rice growth season. However, there are a few studies concerning the relationship between temperature in the fallow season, decomposition rates of rice straw, and thus CH_4 emission levels in the following rice growth season, when regarding cool climate as a condition for the fallow season. In this study, an incubation experiment, a field experiment, and a model evaluation were carried out sequentially to declare relationships between conditions in the fallow season, aerobic decomposition rates and CH_4 emissions. As an attractive CH_4 mitigation option, which needs little additional cost to adopt (Matsumoto *et al*., 2002), the method of shallow autumn tillage—the incorporation of rice straw—is evaluated through this study.

The incubation experiment revealed that the aerobic decomposition rates of rice straw under low temperature conditions modeled to emulate those of the fallow season in the Tohoku region (±5 °C) were very low, at 12-14% over a 24-week incubation. The decomposition rate of rice straw was affected by both temperature and moisture conditions. The high sensitivity of decomposition rate to temperature change indicated that it is very important to improve aerobic decomposition during the early fallow season, still with a relatively high temperature, to reduce the amount of remaining organic matter which underwent aerobic decomposition and became substrate for methanogenesis. Straw decomposition was accelerated by higher soil moisture in this study. This result is not consistent with other previous studies which pointed out that the optimal moisture conditions are intermediate, as in 60% WFPS (Pal *et al.*, 1975; Devêvre and Horwáth, 2000). However, this also shows the importance of oxygen to the process of organic decomposition because the contradiction between the previous studies and this study is assumed to be caused by differences in oxygen usability for microbial activities, even under the same WFPS conditions. Between 39% and 63% of the decomposable carbon under 24 weeks incubation was decomposed in the first 6 weeks in this study. This is because easily mineralizable carbons are decomposed intensively during the early days of incubation (Pal *et al.*, 1975; Sain and Broadbent, 1977). Accuracy and reactivity to changes in conditions were higher for the calculation based on CO_2 production than on those for SOC content and its $\delta^{13}C$ value. Thus, to measure the decomposition rates of rice straw accurately, it is of extreme importance to choose a suitable method in line with the test samples and the study objectives.

For the field experiment, the mitigation effect of shallow autumn tillage was evaluated in an Andisol paddy field in Morioka, Iwate prefecture in Japan. No effects based on the depth of autumn tillage on CH_4 emissions in the following rice growth season were observed in this study. For each treatment of autumn tillage, yearly differences of CH_4 emission were correlated only with the cumulative temperature during the early days after straw incorporation in the previous fallow season. Cumulative temperature, used for analysis of the temperature effect on CH_4 emission in the next year, was calculated as a sum of daily temperatures to 0 °C, because aerobic decomposition proceeded even under 0 °C in the incubation experiment (Chapter III). No correlation between CH_4 emission and cumulative temperature for the same period in a rice growth season was assumed to be caused by the restriction of methanogenesis by other factors such as a deficiency of substrates. This assumption is not a bizarre one because the rice plants were too small to provide additional substrates in the calculated period (Chidthaisong and Watanabe, 1997;

Watanabe *et al*., 1999). On the other hand, numerical simulations of soil water conditions revealed the high water infiltration rate and low water content of the experimental field during the fallow season. It was assumed that the aerobic decomposition rate of incorporated rice straw in the off-rice season might not fluctuate alongside soil water regimes and thus correlated closely with cumulative temperature in this study. Combining this assumption with the result of no effect from autumn tillage depth on CH_4 emission, a hypothesis for a mitigation mechanism of autumn shallow tillage could be proposed: autumn shallow tillage might ameliorate the excess soil water conditions that inhibit the aerobic decomposition rate of incorporated rice straw. This hypothesis implies that the autumn shallow tillage is not effective as a CH_4 mitigation option unconditionally. It also provides important information that the CH_4 mitigation effect from shallow autumn tillage might be determined by the field conditions during the off-rice season.

To assess the hypothesis concerning suitable field conditions for the possibility that shallow autumn tillage may affect CH_4 mitigation during the rice growth season, an evaluation with the DNDC-Rice model was performed. Model evaluation can also be used to evaluate specific CH_4 mitigation options on a regional or national scale. The effect of alternative water management on CH_4 mitigation was assessed with the combination of DNDC-Rice model and GIS database (Fumoto *et al*., 2010). Before evaluation of the mitigation effect of shallow autumn tillage, the DNDC-rice model was validated with the field data from conventional tillage to calculate cumulative CH_4 emission with minimal changes on the set field values. In addition to the measured conditions during the field experiment, a virtual condition for soil texture was set to simulate the effect of shallow autumn tillage under the condition of abundant water in the soil during fallow season. Though the virtual condition of soil texture increased soil water content during the fallow season, no effect was observed on simulated CH_4 emission because of tillage depth in autumn, even under high water content conditions. This result shows two possibilities; an inappropriate assumption that the mechanism of shallow autumn tillage can mitigate CH_4 emission, or a description problem in computational expression for the current model. However, the former possibility cannot be tracked without more accurate field data for soil moisture, soil temperature, farming management and microbial activity. For the purpose of tracking the latter possibility, minor revisions to current DNDC-Rice model have been conducted. The revised model showed a non-significant trend for CH_4 emission to be decreased by shallow autumn tillage only under high soil water content conditions. A factor for the reduction of organic decomposition by soil water conditions was changed in a revised model. In the current model, reduction of organic decomposition by excess soil water is described only as the deficiency of available oxygen (Fumoto *et al*., 2008).

With additional upper limitations to soil water content, organic decomposition would be severely limited under conditions of high soil water content; with a value of at least 0.8 in water filled pore space (WFPS; m^3 m^{-3}) for the revised model. Since there is no supporting theory and study, this revision is nothing more than a trial. However, it pointed out the possibility of an underestimation in the current model for the inhibition of organic decomposition by excess water, and further indicated the possibility of both regional and national evaluation of additional new mitigation options with a process-based biogeochemistry model.

For applying adequate mitigation strategies to CH_4 emission from rice paddies in different regions with different climates, and for variations in soil and farming management, further studies are needed to declare CH_4 mitigation options.

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