Carbon Sequestration and Contribution of CO_2, CH_4 and N_2O Fluxes to Global Warming Potential from Paddy-Fallow Fields on Mineral Soil Beneath Peat in Central Hokkaido, Japan

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Abstract

Three rice paddy fields under farmers' actual management conditions were investigated from May to April at Bibai (43°18′N, 141°44′E), in central Hokkaido, Japan to evaluate the carbon (C) sequestration and contribution of CO_2, CH_4 and N_2O fluxes to a global warming potential (GWP). CH_4 and N_2O fluxes were measured by placing the chamber over the rice plants covering four hills and CO_2 fluxes from rice plants root free space in paddy fields were taken as an indicator of soil microbial respiration (R_m) using the closed chamber method. Annual cumulative R_m ranged from 422 to 519 g C m^{-2} yr^{-1}; which accounted for 54.7 to 55.5 % mainly during the rice growing season. Annual cumulative CH_4 emission ranged from 75.5 to 116 g C m^{-2} yr^{-1} and this contribution occurred entirely during the rice growing period. Annual cumulative N_2O emission ranged from 0.091 to 0.154 g N m^{-2} yr^{-1} and 73.5 to 81.3% of the positive annual N_2O emission observed during the winter-fallow season. Soil C sequestration was estimated as the difference between net primary production (NPP) and C loss through R_m, CH_4 emission and crop C harvest. The soil C sequestration ranged from -305 to -365 g C m^{-2} yr^{-1}, indicating that the C loss could not be compensated for by C input through NPP. Carbon loss was much higher (62 to 66%) in winter-fallow season than growing season. The annual net GWP from the investigated paddy fields ranged from 3823 to 5016 g CO_2 equivalent m^{-2} yr^{-1}. Annual GWP_{CH4} accounted for 71.9 to 86.1% of the annual net GWP predominantly from the rice growing period. These results indicate that CH_4 dominated the rice paddy's net GWP.

***Key words*:** Carbon sequestration; methane; carbon dioxide; nitrous oxide; global warming potential; paddy field.

1. Introduction

Rising atmospheric levels of the greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have caused an increase in radiative forcing of the earth's atmosphere. Agriculture plays an important role in the global flux of these gases [1]. Rice paddies in monsoonal Asia have an important role in the global budget of GHGs [2], but there is still considerable uncertainty in the magnitude of the net fluxes from these ecosystems. Many of the factors controlling gas exchange between rice paddies and the atmosphere are different from those in dryland agriculture and other ecosystems because rice is flooded during most of its cultivation period [2]. Any change in either management or climate/soil conditions will alter the biochemical or geochemical processes, which finally leads to changes in the gas fluxes [3]. For example, incorporating crop straws into soil can increase carbon (C) sequestration [4] but elevate CH_4 fluxes [5]. Lower CH_4 fluxes due to water drainage may increase N_2O fluxes [6]. Studies have shown that a large amount of GHGs are released from paddy fields and that a substantial quantity of CO_2 is sequestered by plants in paddy fields. These two processes help to regulate GHGs in rice paddy ecosystems [7]. Since each GHG has its own radiative potential [8], the estimation of net global warming potential (GWP) in a crop production system must account for all of the three gas constitutes [3].

Net exchanges of CO_2 and CH_4 between rice paddies and the atmosphere are controlled by several biological and physical processes. CO_2 exchange in rice paddies is driven by photosynthesis and autotrophic (plant) and heterotrophic (mainly microbial) respiration [9]. Plant photosynthesis leads to uptake of CO_2 from both the atmosphere and from respired CO_2 emitted by the soil and floodwater. CH_4 is released to the atmosphere by ebullition, diffusion and by transport through rice plant aerenchyma tissue [10]. More than 90% of the total CH_4 emission occurs through the aerenchyma system of the rice plants [11]. For that reason most estimates of gas fluxes in paddy fields have used chambers placed over plants, during measurement [2]. Previous studies considered CH_4 and N_2O but not CO_2 when estimating GWP in paddy fields, because both respiration and photosynthesis activities contributed to CO_2 concentration change in the chamber [12]. There has been a great deal of information to improve our understanding of the processes of C cycle and C storage in soils. This has arisen because of the need to sequester C to overcome global climate change [13]. Carbon sequestration is the process of transferring CO_2 from the atmosphere into the soil through crop residues and other organic solids in a form that is not immediately reemitted. In keeping with definitions suggested by the Intergovernmental Panel on Climate Change [14], sequestration is an increase in the C stock of a pool other than the atmosphere. In attempts to quantify the C sequestration in paddy ecosystems that would accompany changes in agricultural practices, the change in C emissions associated with management practices has largely been overlooked. The GWP of CH_4 and N_2O emissions from paddy soils had been estimated together or separately by numerous researchers [6,15,16]. With regard to the integrated greenhouse effect in CO_2-equivalent of three gases (CO_2, CH_4 and N_2O), the available data are rather scarce. Therefore, the integrated GHG effect under various management practices and the status of “source” and “sink” of paddy fields are essential. Moreover, information regarding annual GHG fluxes and contribution of each GHG to the total GWP from rice growing and fallow periods is insufficient. Furthermore, because actual status of GHG emissions in regional agriculture is quite unclear, methodological research for increasing accuracy of estimations is required. In this study, we present the method of measurements of soil microbial respiration (R_m) from paddy fields. Thus, we have carried out one of the first field-level investigations in paddy field to estimate C sequestration using R_m, direct measured from paddy field. Therefore, the objective of the present studies to estimates the C sequestration in paddy fields and evaluates the contribution of CO_2, CH_4 and N_2O fluxes to GWP.

2. Materials and methods

2.1. Site description and field management schemes

Field investigations were carried out from late May to April at Kita-mura (43°18′N, 141°44′E) near Bibai, located in Central Hokkaido, a major rice-growing area of Japan. We investigated 3 rice paddy fields under farmers' actual management conditions. Three fields of D_1-M (drainage-multiple), D_2-M (drainage-multiple) and D_3-S (drainage-single) were mineral soil dressed peat. Hokkaido is the most recently developed land in Japan. Since its development in the Meiji Era (1867-1911), many of the peatlands in Hokkaido, Japan, were reclaimed as paddies or dry fields [17]. In central Hokkaido, peatland are distributed mainly in the lowlands along the main river, Ishikari. Especially after the year 1945, most of the Ishikari peatlands have been used for paddy cultivation according to the systematic development plan of the Japanese Government. In the 1960s, the peat soils (studied area) were drained, top dressed with about 30 cm of mineral soil, and turned into productive crop fields [18]. The mineral soil (dressing) thickness of soil-dressed peatland fields of D_1-M, D_2-M and D_3-S were 20±4.2, 29±5.4 and 29±5.4 cm, respectively. All of the fields under single cropping yr^{-1} and a paddy-fallow-paddy crop rotation as system. Before the experiment, paddy rice had been cultivated in all the fields for approximately consecutive 10 years. The prevailing local practice for rice straw management is to leave rice straw on paddy fields after harvest in autumn and to incorporate the straw into the soil in the following spring (early May) by plowing. The study area has a cold climate with a long period of snow cover in winter. During the winter-fallow period (October to April), between harvest and the next year's planting, the rice straw was left on the unplowed fields. From November to April, crop residues were covered by deep snow with subfreezing air temperatures. We observed that a variable amount of rice straw leftover on the fields resulted from different yields of the previous year's paddy rice crops; farmers collected only grain and combine harvesters left short pieces of rice straw on the soil surface as spreading on fallow fields. In central Hokkaido, as we mentioned above, the kind and abundance of leftover organic materials was mainly from rice plants, no other weeds or/if any it was very small and negligible. In winter-fallow period, the duration between the rice harvest in autumn (end of September) and the first snowfall was about 45 days. This short duration and gradually decreasing air temperature is not favorable for weed growth. Furthermore, the fields remain under deep snow cover until the next spring (first week of April). The selected fields included different water management practices. Multiple drainage (frequency of drainage, two times) was done in D_1-M and D_2-M, and single drainage (mid-season) in middle of growing season was done in D_3-S field. The duration of each drainage was 10 days. All fields were finally drained for harvest at the end of the growing season. The difference in water management practices among the fields might have governed mainly due to differences in amounts of leftover rice residues and soil condition. Drainage practices were commonly selected to avoid strong reductive conditions and to promote the decomposition of leftover rice straw. Paddy field D_3-S practiced single drainage even though this field received the highest amount of previous crop residues. However, the frequency of drainage depends on field conditions. Some physical and chemical properties of the investigated field's soils are presented in Table 1. Detailed information on amount of leftover straw on fields and other management practices are presented in Table 2.

2.2. Experimental layout and approach

Three rice-paddy fields were selected under farmers' actual management conditions. Each field was used as treatment, and had three measurement positions. Field D_1-M, D_2-M and D_3-S received different amounts of leftover rice straw from previous year's rice crop. We considered three treatments and three chambers per field, i.e., three treatments (three fields) and three replications (three chambers per field). The distance between each of the field sites was about 500–1000 m. Three chambers (three replicates) were placed in each field at an equal distance of 30 m. Immediately after transplantation, an aluminum chamber base of 61 cm × 31 cm × 7 cm (length × width × height), which has 1 cm × 2.5 cm (width × deep) water groove on inner side, was installed in the waterlogged soil. The base groove was filled with water if the field-water table dropped below the groove level. To avoid soil disturbance during gas collection, boardwalks were constructed from border dikes across each sampling site. During the cropping period, all observations were made from the boardwalks to avoid disturbing the soil.

2.3. CH_4 and N_2O gas sample collection and analysis

A closed-chamber method [5] was used to collect gas from the experimental fields. Transparent, rectangular gas-sampling chambers of 60 cm × 30 cm × 100 cm (length × width × height) were constructed using 5-mm-thick acrylic sheets and placed on base over the rice plants covering four hills in the paddy fields. To prevent pressure gradients between the interior and exterior of the chambers during flux measurement and gas sampling, a plastic lightweight bag was affixed inside. To measure the inside temperature, a digital electronic thermometer was attached inside the chamber with a silicon cork. A silicon tube with a three-way stopcock was also attached to each chamber with a silicon cork for gas sampling. Every sampling event was replicated three times. Sampling was carried out three to four times per month within 10:00 h to 15:00 h on each sampling day. The same approach was used at each field site on each sampling date. At each sampling time, gas was sampled at 0, 10, and 20 min using a 25-mL polypropylene syringe and was transferred into a 20-mL vacuum vial with a hypodermic needle. CH_4 concentrations of the collected gas samples were analyzed in the laboratory by a gas chromatograph equipped with a hydrogen flame-ionized detector (FID, SHIMADZU GC-8A, Shimadzu Corporation, Kyoto, Japan) while N_2 (flow rate: 100 kPa), H_2 (flow rate: 50 kPa), and zero air (flow rate: 50 kPa) were used as the carrier, fuel, and supporting gas, respectively. Column and injector/detector temperature were set at 70 °C and 130 °C, respectively. Cylinder for CH_4 standard of 2.0 and 10.0 ppmv, obtained from Hokkaido Air Water Inc, Sapporo, Japan, was used as the primary standard, and it had an injection volume of 1 mL. N_2O concentrations were determined with a gas chromatograph equipped with a ^{63}Ni electron capture detector (ECD, SHIMADZU GC-14B, Shimadzu Corporation, Kyoto, Japan). N_2 was used as the carrier gas and the flow rate was maintained at 400 kPa. Column, injector, and detector temperatures were set at 60, 250, and 340 ºC, respectively. Calibration was performed using N_2O standard gas at a concentration of 0.3 ppmv (Hokkaido Air Water Inc, Sapporo), and an injection volume of 1 ml.

2.4. Soil Microbial respiration (R_m) measurement

CO_2 fluxes were taken from rice plants root free space in paddy fields as an indicator of soil microbial respiration [19]. In general, distribution of rice roots in the subsurface soil below 20 cm depth and the horizontal distribution of roots in 15 cm distance [20]. Immediately after transplantation, rice seedlings of 1-m^2 from three places of each field were plucked up. An aluminium chamber base of 31 cm × 31 cm × 7 cm (length × width × height), which has 1 cm × 2.5 cm (width × deep) water groove in inner side, placed in the middle of the rice plants root free space to set the chamber on them. The distance between the edge of chamber base and the rice plants was 69 cm in around. Therefore, the chamber base inside was free from rice roots. The base groove was filled with water to make the system air-tight when field was in drained condition. Transparent rectangular chambers of 30 cm × 30 cm × 60 cm (length × width × height) made by 3-mm-thick acrylic sheets was used for R_m measurement in the paddy fields. Three chambers were placed in each field with equal distance (three replicates). Chamber was covered by dark sheet during R_m measurement. Every sampling event was replicated three times. Sample collection procedures and time were identical to gas sample collection for CH_4 and N_2O but samples of air within the chamber were taken with a 50 mL polypropylene syringe at 0 and 6 minute after setting up chamber and transferred in to a 400 mL Tedlar® bag through a silicon tube attached to the top of the chamber. R_m (CO_2) was analyzed within 2 h after collection with an infrared gas analyzer (FUJI ZFP-9, Fuji Electric Co., Ltd., Tokyo, Japan).

2.5. Gas flux calculation

Gas fluxes were calculated from the linear increase or decrease of gas concentration in the chamber over time, using the following equation:

$$F\ (\text{mg C m}^{-2}\ \text{h}^{-1}) = \rho \times V/A \times \Delta c/\Delta t \times 273/T \times \alpha \qquad (1)$$

where, F is the gas flux; ρ is the density of gas at the standard condition (R_m as CO_2 =1.96 × 10^6 mg m^{-3}, CH_4 = 0.716× 10^6 mg m^{-3}, and N_2O = 1.97× 10^6 mg m^{-3}); V (m^3) and A (m^2) are the volume and bottom area of the chamber, respectively; Δc/Δt (m^3 m^{-3} h^{-1}) is the gas concentration change in the chamber during a given period; T is the absolute temperature (K); and α is the conversion factor for gas (CO_2 = 12/44, CH_4 = 12/16 and N_2O = 28/44). A positive flux indicates the emission of gas from soil into the atmosphere, and a negative flux indicates its uptake from the atmosphere. The cumulative fluxes were calculated assuming the existence of linear changes in gas emissions between two successive sampling dates:

$$\text{Cumulative gas emission} = \sum_{i=1}^{n-1} (R_i \times D_i) \qquad (2)$$

where, R_i is the mean gas flux (mg m^{-2} d^{-1}) of the two sampling times, D_i is the number of days in the sampling interval, and n is the number of sampling times. The cumulative gas flux of individual gases is 121 days for the rice growing season and it was 211 days for winter fallow season. Gas samples collections were not conducted during May due to land preparation and transplantation.

2.6. Soil and plant sample analysis

Initial soil samples (0-10 cm depth) were collected by hand using a stainless-steel auger and analyzed for chemical properties. Undisturbed 100 cm^3 soil cores and disturbed samples (PVC bag; about 500 g) were collected from the depths of 0-10 cm. Un-disturbed core samples were used to measure the bulk density. Bulk density ρ_b (g cm^{-3}) was obtained by ρ_b= Ms/100, where Ms (g) is the mass of dry solids determined after drying the soil sample to constant weight at 105 °C in a 100 cm^3 core. Disturbed samples were air dried for more than 3 weeks in the laboratory, and then passed through a 2-mm sieve to remove coarse materials. Soil texture was determined by the pipette method. Soil pH was determined with a glass electrode pH meter (HORIBA pH meter F-8, Horiba, Kyoto, Japan) in a supernatant suspension of 1:2.5 soil:water mixture. To record the amounts of residues from the previous year's crop, rice straw for each field was collected from three 1-m^2 quadrates and dried in an oven at 70°C for 3 days. Residue was considered as the above ground harvested parts of rice plant, except grain. Dried soil and plant samples from each field were ground (e.g., to powder) by hand with a mortar and pestle to determine total C concentrations with a C–N analyzer (vario MAX CNS, Elementar Analysensysteme GmbH, Langenselbold, Germany).

2.7. Net primary production (NPP) estimation

Net primary production which includes above and below ground biomass of rice plant of the investigated fields was estimated. Plant samples of three 1-m^2 quadrates from each field were collected by hand immediately before the harvest [5]. Root sample was taken from the top 0-20 cm depth of soil. Aboveground samples were separated into grains, straw and stubble. Those plant samples were dried and analyzed in the same way as described in the soil and plant sample analysis.

2.8. Soil C sequestration (CS) estimation

Soil C sequestration was estimated to correspond to the difference between NPP and C loss through soil microbial respiration (R_m), CH_4 emission and crop C harvest. CS (g C m^{-2}) of each field was estimated as follows (Fig. 1):

$$CS_g = NPP – (R_m + CH_4 \text{ emission} + \text{grain harvest}) \text{ for rice growing period} \quad (3)$$

$$CS_f = – (R_m + CH_4 \text{ emission} + \text{straw harvest}) \text{ for winter-fallow period} \quad (4)$$

For one year:

$$CS_g + CS_f = NPP - (R_m + CH_4 \text{ emission} + \text{grain harvest} + \text{straw harvest}) \quad (5)$$

where CS_g and CS_f are the C sequestration during rice growing and winter-fallow period, respectively; Rice grain and straw yields of three 1-m^2 quadrate were investigated. Grain and straw carbon was calculated from dry weight and carbon content.

2.9. Global warming potentials (GWP) estimation

Global warming potential (GWP) is defined as the direct and indirect effects of cumulative radiative forcing integrated over a period of time from the emission of a unit mass of gas relative to some reference gas, CO_2 as the reference gas [21]. The GWP (g CO_2 equivalent m^{-2} $season^{-1}$) which is CO_2 based emission was computed from the GHG emissions of each field, using a 100-year time horizon, as recommended by IPCC [8] (conversion factors of 1 for CO_2, 28 for CH_4 and 265 for N_2O). GWP was calculated as follows:

$$\text{Net GWP} = CO_2 \text{ GWP} + CH_4 \text{ GWP} + N_2O \text{ GWP} \quad (6)$$

Where, CO_2 GWP = – (CS + CH_4) (g CO_2-C m^{-2} $season^{-1}$) × (44/12);

CH_4 GWP = CH_4 (g CH_4-C m^{-2} $season^{-1}$) × (16/12) × 28; and

N_2O GWP = N_2O (g N_2O-N m^{-2} $season^{-1}$) × (44/28) × 265.

2.10. Statistical analysis

Statistical differences were performed by Tukey's multiple comparisons test by using Excel Statistics version 4.0 (Esumi Co. Ltd., Tokyo, Japan).

3. Results

3.1. Climatic conditions

Meteorological data during the rice growing and winter-fallow periods were recorded and presented in Fig. 2 a & b. During the rice-growing period (late May–September), the mean air temperature was 17.9°C (range: 12.9 to 21.1°C), which was 5.1°C lower than the average soil temperature at a depth of 3 cm. The total precipitation during rice-growing period was 611 mm, accounting for 48% of the annual total precipitation (1265 mm). The average air temperature after harvest to before the first snowfall (October–late November) was 8.2°C (range: 0.80 to 14.2°C). During the snowy period (late November–late April) the average air temperature was -2.2°C (range: -13.6 to10.2°C) and snow depth averaged 58 cm (range: 0 to 120 cm). The mean annual temperature was 7.94°C, which was 0.8 °C higher than the 10-year average and the annual total precipitation was 87.5 mm higher than the 10-year average.

3.2. Greenhouse gas fluxes (R_m, CH_4 and N_2O)

The cumulative R_m of the three paddy fields varied during the growing period (Table 3) and was ranged from 234 to 284 g C m^{-2} growing $season^{-1}$. The cumulative R_m during the rice growing season was 54.7 to 55.5% of the annual total R_m. The cumulative R_m (g C m^{-2} $season^{-1}$) of the three paddy fields, D_1-M, D_2-M and D_3-S was ranged from 188 to 235 during winter-fallow period. The annual cumulative R_m of D_2-M field showed the highest rate (519) and the lowest from D_3-S D_3-S (422) (Table 3). The CH_4 emission rate was much higher in rice growing period than winter-fallow and the contribution to the total annual emission was 100% from the rice growing period (Table 3). The cumulative CH_4 emission during rice growing season from paddy fields was ranged from 75.5 to 116 g C m^{-2} (*This cumulative CH_4 emission data* *was published in Naser et al., 2018, Atmosphere, 9, 212-MDPI*). Non significant variation among the gas fluxes in growing season, whereas it was significantly differed (P < 0.01) in winter-fallow season, even though the fluxes of CH_4 during the winter-fallow period was very low or tended to be uptake. In winter-fallow, paddy fields D_2-M and D_3-S fields showed emission, on the other hand, D_1-M field showed uptake (-0.019 g C m^{-2}). The annual total CH_4 emission showed similar trend as like as the growing period (Table 3). Very low N_2O flux was observed during the rice growing and winter-fallow period (Table 3) and they were varied significantly (P <0.05 and P <0.01 for rice growing and winter-fallow period, respectively). The cumulative N_2O fluxes (g N m^{-2} season^{-1}) of the three paddy fields during the rice growing period showed low emissions, which ranged from 0.003 to 0.036 and during the winter-fallow period showed low uptake as well as emissions, which ranged from -0.013 to 0.118. Annual basis N_2O flux (g N m^{-2} yr^{-1}) was highest in D_2-M (0.154) followed by D_1-M (0.091) and D_3-S (0.016) (Table 3). The N_2O emission rate was much higher in winter-fallow season than growing season and the contribution to the total annual emission was 73.5 to 81.3% from the winter-fallow season.

3.3. Soil C sequestration (CS)

The net primary production (NPP) at different paddy fields varied from 499 to 530 g C m^{-2} (Table 4). The NPP of D_1-M was lower (499 g C m^{-2}) than those of the other fields in this study and other two fields showed almost similar NPP 529 and 530 g C m^{-2}. The amount of C harvested as grain ranged from 266 g C m^{-2} to 298 g C m^{-2}, accounting for 53 to 56% of the respective NPP. There was an irregular trend in amount of NPP and grain yield among the variables such as rice variety, inorganic N fertilizer addition, straw residue and water regime. And non significant relation was found with added inorganic N fertilizer or straw residue on

NPP and grain yield. We calculated one year C sequestration from paddy fields including growing and winter-fallow season (Table 5). The negative value of CS indicates C loss from the soil to the atmosphere. The losses of organic C through R_m, CH_4 emission and C harvested as grain exceeded the corresponding NPP values for all the paddy fields. As a result, soil C sequestration was negative (ranged, -305 to -365 g C m^{-2} yr^{-1}). During the rice growing and winter-fallow season all the fields showed net sources of C (Table 6). The status of C losses rather than C sequestration during winter-fallow period compared with growing period showed an increment in C losses from 62 to 92%. The negative C sequestration rate or C losses was much higher in winter-fallow season than growing season and the contribution to the annual C losses was 62% to 66% from the winter-fallow season.

3.4. Combined climatic impact of CO_2, CH_4 and N_2O

The calculated GWP values for all suites of GHGs are presented in Table 7. Positive GWP value indicated global warming and negative GWP value indicated mitigation. The GWP_{CO2} of three drainage practiced fields showed positive GWP (ranged, 3.52 to 196 g CO_2 equivalent m^{-2} growing $season^{-1}$). During winter-fallow season all fields acted as sources of GWP_{CO2}. As a consequence, the GWP_{CO2} varied from 689 to 861 g CO_2 equivalent m^{-2} winter-fallow $season^{-1}$. The GWP_{CO2} emissions during winter-fallow period from D_1-M, D_2-M and D_3-S fields were equivalent to 85, 81 and 99% of the annual GWP_{CO2}, respectively.

The GWP_{CH4} (g CO_2 equivalent m^{-2} growing $season^{-1}$) was higher in D_3-S field (4312), this field received highest amount of rice residue (Table 7). D_1-M and D_2-M showed approximately 34–35% lower GWP_{CH4} emissions than single drainage field, D_3-S. GWP_{CH4} during winter-fallow period was very low or tended to be uptake. In seasonal aspect, GWP_{CH4} contributed 100% to the annual GWP_{CH4} mainly from the rice growing period.

The GWP_{N2O} values of three drainage practiced fields D_1-M, D_2-M and D_3-S during the rice growing period were 10.2, 15.1 and 1.36 g CO_2 equivalent m^{-2}, respectively (Table 7). The value of GWP_{N2O} from D_1-M and D_2-M fields was 8 and 11-fold, respectively, as high as that from single drainage practiced field (D_3-S). The status of GWP_{N2O} during winter-fallow season compared with growing season showed an increment in N losses from 171 to 284%. In seasonal aspect, GWP_{N2O} contributed 73 to 79% to the annual GWP_{N2O} from winter-fallow season.

The annual net GWP (g CO_2 equivalent m^{-2} yr^{-1}) from D_1-M and D_2-M fields showed comparable value of 3823 and 3990, respectively, on the other hand, 5016 from single drainage practiced field (D_3-S) (Table 8). Therefore, relative to the D_3-S field, the net annual GWP was 23.8% smaller for the D_1-M and 20.4% smaller for the D_2-M fields. The net GWP (g CO_2 equivalent m^{-2} $season^{-1}$) values from three paddy fields ranged from 2978 to 4317 from growing season and 699 to 911 from winter-fallow season. On the basis of seasonal net GWP, the contribution to the annual net GWP was 77 to 86% from the growing season.

4. Discussion

4.1. Soil C sequestration

The C sequestration values in this study ranged from –305 to –365 g C m^{-2} yr^{-1}, indicating that C gained, resulting from NPP were not sufficient to offset C losses from paddy soils by R_m, CH_4 emission and C harvested as grain (Table 6). Thus, these paddy-fallow ecosystems were net sources of atmospheric CO_2. Paustian *et al.* [22] reported that the net difference between the photosynthetically-fixed CO_2 that enters the soil as plant residues and the CO_2 that is emitted from decomposition is much smaller. This difference determines the net C balance of the ecosystem, i.e., whether it is a source or sink for CO_2. The CO_2 fixed in plant biomass through photosynthesis can be stored in the soil as organic C by converting plant residue into soil organic matter after the residue is returned to the soil [23].

The differences in C sequestration between the three paddy fields in this study were related to the crop residue management and drainage practice [24]. Crop residues addition influence C sequestration in two ways: one, carbon storage is done due to the addition of rice straw to soil, on the other hand, methane emission is enhanced with rice straw addition. Moreover, rice straw residues enhance both R_m and CH_4 emissions [25,5]. Drainage and flooding also affect the condition of organic matter decomposition (aerobic or anaerobic), resulting in the change of responsible microorganisms [26]. Rees *et al.* [27] reported that some management practices are likely to have a negative impact on C sequestration.

Our estimated C sequestration values (ranged, –305 to –365 g C m^{-2} yr^{-1}) were larger than the Hu *et al.* [28] estimated C sequestration values (–147 to –222 g C m^{-2} yr^{-1}) from onion-fallow field in Mikasa, central Hokkaido, Japan. Moreover, the values of C sequestration in this study were also higher than the reported C sequestration from grassland, onion, soybean, wheat and maize fields in Mikasa were –235, –348, –287, –255 and –227 g C m^{-2} $period^{-1}$ (late March to mid December), respectively [29]. The result obtained by Koizumi *et al.* [30] in Japan indicated that the C sequestration value in upland rice and barley cropping ecosystems, in peanut and wheat cropping ecosystems, and dentcorn and Italian ryegrass cropping ecosystems were –378, –416 and –630 g C m^{-2} yr^{-1}, respectively. Koizumi [31] also reported that C budgets were different between the single-and double-cropping systems. The annual C balance was estimated to be -270~-320 g C m^{-2} for the upland single-cropping fields (Upland rice, corn, peanut), and -160~-270 gC m^{-2} for the upland double-cropping fields (Upland rice-barley, corn-barley, peanut-wheat) in Tsukuba, Japan. In this study, paddy fields during the rice growing season indicating C losses from soil. Our results contrast with the findings of Liping & Erda [32], they reported that, paddy soils store more C or avoid the C emission than the upland soils. In addition, Xiao *et al.* [7] reported that, rice paddy ecosystems may function as a significant CO_2 sink during the growing season. Paddy fields have been generally managed intensively for the better yield of rice, and many of the field management closely relate to the C cycling in the paddy ecosystem [26].

This study shown that different types of management can contribute at different rates of C losses from soil. Similar result also observed by Rees *et al.* [27]. Sainju *et al*. [23] reported that management practices can increase CO_2 emission from the soil by disrupting soil aggregates, increasing aeration, incorporating plant residue, and oxidizing soil organic C. They also reported that CO_2 emissions from soil to atmosphere is the first process of C loss from the soil and provides an initial indication of C sequestration in the soil when management practices changes the soil organic C. A range of C sequestration studies have been published in the past decade, and all of those mainly from upland cropping, were conducted over one year or longer. Although it is not possible to make direct comparisons between the data describing C sequestration in this study and reported values, as we calculated soil C sequestration using the C budget method.

The net primary production in this study varied from 499 to 530 g C m^{-2} and this variation is non significant (Table 4). The values were higher than most of the reported NPP values for maize, grass, soybean, onion and wheat in Mikasa, central Hokkaido fields were 180, 218, 304, 349 and 454 g C m^{-2}, respectively [29]. Omura *et al.* [33] estimated NPP (ground truth data) from paddy fields of Toyama, Akita, Niigata and Yamagata in Japan were 1445, 1563, 1572 and 1738 g m^{-2} (dry matter wt.) respectively. Those values were higher than that of our investigated NPP 1182 to 1306 g m^{-2} (dry matter wt.). For example, Shinano *et al.* [34] reported that NPP value for 100 kg N ha^{-1} fertilized rice and maize in Hokkaido university farm were 632 and 812 g C m^{-2}, respectively, whereas it was 170, and 337 g C m^{-2}, respectively for these crops in the absence of N fertilization. Moreover, Lamptey *et al.* [35] reported that NPP value for 300 kg N ha^{-1} fertilized maize was 859 g C m^{-2}, whereas it was 455 g C m^{-2} in the absence of N fertilization. Those values of NPP from N fertilized rice and maize was higher than that of our investigated fields. The amount of C harvested as grain ranged from 266 to 298 g C m^{-2}, accounting for 53–56% of the respective NPP. In other words, about 44 to 47% of the NPP was incorporated into soil. NPP is amount of C fixation by vegetation and an important parameter to estimate C balance [36].

4.2. Greenhouse gas fluxes (R_m, CH_4 and N_2O)

The activity of the soil microbial populations must have differed considerably to account for the observed water and residues managements. Relationship between the amount of rice residue and seasonal total R_m which is in agreement with the findings of Li *et al.* [3]. However, single drained fields D_3-S showed approximately 17 to 21% lower R_m than that of multiple drained fields D_1-M and D_2-M, respectively. Management practices play an important role in influencing losses of C by respiration. Respiration by soil microflora and fauna also contribute a major portion of CO_2 emission from the soil observed by Sainju *et al.* [23].

We presume that the differences in soil microbial activity occurred mostly during the drainage as a result of anoxic soil in the submerged conditions versus the aerated soil status during drainage period [37]. Microbial respiration (R_m) were recorded from paddy soils in this study shows an almost two fold variation in fluxes, ranging between 422 and 519 g C m^{-2} yr^{-1} (Table 3), indicating the rates of R_m altered by agricultural management operations like water regime [27]. The R_m from D_1-M, D_2-M and D_3-S (497, 519 and 422 g C m^{-2} yr^{-1}, respectively) fields was higher than the reported [28] R_m for fertilized bare onion fields (188 to 222 g C m^{-2} yr^{-1}) in Mikasa, Hokkaido. Moreover, Mu *et al.* [29] reported that R_m from grassland, wheat, onion, maize and soybean fields in Mikasa, Japan were 301, 328 to 568, 393, 346 and 464 g C m^{-2} $period^{-1}$ (late March to mid December), respectively.

Compared to the D_3-S field than the D_1-M and D_2-M fields, the annual cumulative CH_4 emissions were about 52% higher in D_3-S field due to differences in crop residue and drainage effect. Methane emissions increased with increased rice straw addition, which matches the results of many researchers [38,39,15] and our previous study [5]. The D_3-S field showed the maximum efficiency of the CH_4 emissions, which resulted in the large

CH_4 emissions under the single drainage system compared to double drainage (D_1-M and D_2-M) fields during the rice growing season. Lesser residues and multiple drainage systems reduce the CH_4 emissions by 33 to 34% compared with single drainage. The published data collection of CH_4 emissions from the major rice growing areas of Asia shows that the average CH_4 flank with single and multiple drainage, is 60 and 52%, respectively. So, organic amendments and the water regime are the two variables controlling the CH_4 flux in the rice growing season.

We found very low N_2O emission during the rice growing season, even though those fields received huge amount of rice straw and different water management. Straw incorporation tended to decrease N_2O emissions during the rice-growing season [42,43]. The observed decreases in N_2O during the rice-growing season in the presence of straw incorporation may be explained by the following: the decomposition of crop residues with a high C:N ratio can enhance microbial N immobilization, resulting in less available N for nitrification and denitrification and consequently decreased N_2O emissions [44,45]. In fact there is some evidence that N_2O emissions from rice fields could even be reduced by high straw amendments [46,47,48]. In contrast, incorporation of plant residues has frequently been observed to promote N loss [49,50]. Granli & Bøckman [51] reported that when soil is submerged continuously with a water layer, nitrification proceeds slowly, while denitrification proceeds increasingly towards N_2, and N_2O diffusion in soil is severely hindered by the water layer. It has been generally thought that the emission rate of N_2O from rice paddy field to the atmosphere was very low. Generally, low N_2O fluxes are found during flooded periods, whereas high N_2O fluxes are found during temporal drained periods [52,53,54,55].

In this study, investigated paddy fields were under farmers' actual management conditions where various water regime and different amount of crop residue from previous crop were present. Although water management that included multiple and single drainage might have interrupted the trend of GHGs emission in this study. Hadi *et al.*[56] observed that, the reductions of GHGs emission from Japanese peaty and alluvial paddy soil due to intermittent drained were about 32 and 37%, respectively. Our results do not refute the findings of other studies where water management was a key factor in reducing GHGs emissions from paddy. But we emphasize that the environmental conditions of central Hokkaido in association with crop-residue management favored GHGs release into the atmosphere [5,29]. However, the fact remains that the mineral-soil dressing on peat could have a significant impact to suppress GHGs emission from beneath the peat reservoir.

4.3. Combined climatic impact of CO_2, CH_4 and N_2O

Research on GWP of paddy ecosystem, including rice growing and fallow period is very limited. Earlier Zou *et al.* [57] calculated GWPs using IPCC factors [58] to assess the combined climatic impacts only from CH_4 and N_2O emissions in rice paddies under various agricultural practices and not CO_2 emission in their estimation. Moreover, Xiao *et al.* [7] estimated net GWP (g CO_2 equivalent m^{-2} yr^{-1}) in paddy field where the GWP of N_2O and CH_4 emission estimation procedure were quite similar to the values estimation in the present study (Table 7). Thus, the major difference in the net GWP between their study and ours resulted exclusively from the difference in GWP_{CO2} estimation. In our study for computation of GWP_{CO2} emission were based on the C budget method. Robertson *et al.* [59] and Six *et al.* [60] observed that the change in soil organic C (SOC) or soil respiration should be measured for accounting of GWP of soils. Six *et al.* [60] and Yu & Patrick [61] computed the GWP of different soils by measuring the changes in SOC storage. The IPCC [8] also suggest calculating GWP using the same approach.

The annual net GWP values from three paddy fields in this study were higher than those for paddy and upland crop in other studies. Hadi *at el.* [56] reported that net GWP from intermittently drained paddy fields in South Kalimantan, Indonesia was 2091 (g CO_2 equivalent m^{-2} growing season^{-1}). Moreover, Wu *et al.* [62] reported that the net GWPs was 890 g CO_2 -equivalent m^{-2} yr^{-1} for the field which was flooding during the rice season but with drainage during the midseason and harvest time. Mu *et al.* [29] estimated net GWP for seven upland cropping systems in Mikasa, central Hokkaido, Japan ranged from 749 to 1790 (g CO_2 equivalent m^{-2}-late March to mid December), where CO_2 emission contributed to 84 to 99% of the net GWP. Those values are lower than that of our study. The trend of increase in net GWP mainly govern by the trend of CH_4 emission from the studied fields. The fields with positive net GWP in this study showed annual GWP_{CH4} accounted for 71.9 to 86.1% of the annual net GWP. In seasonal aspect, GWP_{CH4} contributed 100% to the annual net GWP mainly from the rice growing period. On the other hand, GWP_{CO2} and GWP_{N2O} contributed 81 to 99% and 73 to 79%, respectively from winter-fallow season. Methane has been reported to account for 95% of total CO_2-equivalent emissions from paddy fields based on GWP [63]. Xiao *et al.* [7] reported that the annual net GWP (g CO_2 equivalent m^{-2}) in paddy field was estimated to be 640 to 1124, and CH_4 emission contributed to 90 to 99% of the net GWP. Those results indicated that CH_4 dominated the rice paddy's positive net GWP, whereas CO_2

dominated for the upland crops. The proportion of contribution (%) from individual GHG basis GWP to net GWP of CO_2, CH_4, and N_2O were 13.8 to 26.5, 71.9 to 86.1 and 0.13 to 1.61, respectively. This indicates that CH_4 was a major GWP contributor in paddy field and was regulated by management practices especially residue and water regimes. However, the net GWP was dominated by CH_4 emissions, consistent with the findings of previous studies [64,65,66].

5. Conclusion

Paddy-fallow cropping systems could be sources of atmospheric CO_2, CH_4 and N_2O. C sequestration showed negative values i.e., C loss for all the paddy fields. C loss can not be compensated for by NPP due to the impact of residue management followed by water management on C fluxes (CO_2-C and CH_4-C). The annual GWP_{CH4} accounted for 69.4 to 84.6% of the annual net GWP and this contribution occurred entirely during the rice growing period. These results indicate that CH_4 dominated the rice paddy's net GWP. The method of CS estimation described in this study will help to make progress in measurements of C input and loss from paddy soils and will provide us with more accurate ways of assessing changes in soil C stocks and, thus, should reduce the uncertainties that underlie predictions of soil C stocks in paddy ecosystems. The present study implied that paddy field is more potent to loss of C rather than C store. However, management practices like residue and water regime may be the major options to control C budget in paddy-fallow ecosystems.

Author Contributions: H.M.N., O.N. and R.H. conceived and designed the experiments; H.M.N. and O.N. performed the experiments; H.M.N., O.N. and S.S. analyzed the data; all of the authors contributed reagents/materials/analysis tools and wrote the paper.

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References

1. Gregorich EG, Rochette P, Bygaart AJV, Angers DA. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil Till. Res*. 2005; 83: 53–72.

2. Miyata A, Leuning R, Denmead OT, Kim J, Harazono Y. Carbon dioxide and methane fluxes from an intermittently flooded paddy field. Agril. Forest Meteorol. 2000; 102: 287–303.

3. Li C, Mosier A, Wassmann R, Cai Z, Zheng X, Huang Y, Tsuruta H, Boonjawat J, Lantin R. Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. Global Biogeochem. Cycles. 2004; 18: 1–9, GB1043.

4. Sass R. Spatial and temporal variability in methane emissions from rice paddies: Implications for assessing regional methane budgets. Nutr. Cycle Agroecosyst. 2002; 64: 3–7.

5. Naser HM, Nagata O, Tamura S, Hatano R. Methane emissions from five paddy fields with different amounts of rice straw application in central Hokkaido, Japan. Soil Sci. Plant Nutr. 2007; 53: 95–101.

6. Towprayoon S, Smakgahn K, Poonkaew S. Mitigation of methane and nitrous oxide emissions from drained irrigated rice fields. Chemosphere. 2005; 59: 1547–1556.

7. Xiao Y, Xie G, Lu C, Ding X, Lu Y. The value of gas exchange as a service by rice paddies in suburban Shanghai, PR China Agriculture. Ecosyst. Environ. 2005; 109: 273–283.

8. IPCC—Intergovernmental Panel on Climate Change. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 87 pp.

9. Minamikawa K, Sakai N, Hayashi H. The effects of ammonium sulfate application on methane emission and soil carbon content of a paddy field in Japan. Agr. Ecosyst. Environ. 2005; 107: 371–379.

10. Wang C, Lai DYF, Sardans J, Wang W, Zeng C, Peñuelas J. Factors related with CH_4 and N_2O Emissions from a paddy field: Clues for Management implications. PLOS ONE | 2017; DOI:10.1371/journal.pone.0169254: 1-23.

11. Qin X, Li Y, Wang H, Li J, Wan Y, Gao Q, Liao Y, Fan M. Effect of rice cultivars on yield-scaled methane emissions in a double rice field in South China. Journal of Integrative Environmental Sciences. 2015; 12: 47-66.

12. Yu K, Chen G. Reduction of global warming potential contribution from a rice field by irrigation, organic matter, and fertilizer management. Global Biogeochem Cycles. 2004; 18: 1–10, GB3018.

13. Fang J, Yu G, Liu L, Hu S, Chapin III F.S. Climate change, human impacts, and carbon sequestration in China. PNAS. 2018; 115(16): 4015–4020.

14. Watson RT, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ, Eds. Land Use,

Land-Use Changes, and Forestry. A Special Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York. 2000.

15. Wang W, Lai DYF, Sardans J, Wang C, Datta A, Pan T, Zeng C, Bartrons M, Peñuelas P. Rice straw incorporation affects global warming potential differently in early vs. late cropping seasons in Southeastern China. Field Crops Res. 2015; 18: 42–51.

16. Ali MA, Hoque MA, Kim PJ. Mitigating Global Warming Potentials of Methane and Nitrous Oxide Gases from Rice Paddies under different irrigation regimes. AMBIO, 2013; 42: 357–368.

17. Zhou J, Tachibana H. Land Use/Cover Changes in Sarobetsu Mire, Hokkaido, since circa 1900. Reports of the Taisetsuzan Institute of Science. 2002; 36: 1–12.

18. Itoh S, Komada M, Kimiwada K, Awasaki H. Experiment of restoring high-moor plant community based on ground water environment of peatland. Research bulletin no. 173 of the Hokkaido National Agricultural Experiment Station. 2001.

19. Hanson PJ, Edwards NT, Garten CT, Andrews JA. Separating root and soil microbial contributions to soil respiration. A review of methods and observations. Biogeochem. 2000; 48: 115–146.

20. Jeon W.-T. Rice root distribution and rice-based cropping systems for sustainable soil–rhizosphere management. International Workshop on Sustained Management of the Soil-Rhizosphere System for Efficient Crop Production and Fertilizer Use. Land Development Department, Bangkok 10900, Thailand, 16–20 October, 2006.

21. Miller BG. Coal Energy Systems - Page 116. Elsevier Academic Press. 30 Corporate Drive, Suite 400, Burlmgton. 2005; MA 01803, USA.

22. Paustian K, Six J, Elliot ET, Hunt HW. Management options for reducing CO_2 emission from agricultural soils. Biogeochem. 2000; 48: 147–163.

23. Sainju, U.M.; Jabro, J.D.; Stevens, W.B. Soil Carbon Dioxide Emission as Influenced by Irrigation, Tillage, Cropping System, and Nitrogen Fertilization. J Environ Qual. 2008; 37(1); 98–106. doi: 10.2134/jeq2006.0392.

24. Islam SF, Groenigen JW, Jensen LS, Sander BO, Neergaard A-de. The effective mitigation of greenhouse gas emissions from rice paddies without compromising yield by early-season drainage. Science of the Total Environment. 2018; 612: 1329–1339.

25. Ibrahim M, Cao C-G, Zhan M, Li C-F, Iqbal J. Changes of CO_2 emission and labile organic carbon as influenced by rice straw and different water regimes. Int. J. Environ. Sci. Technol. 2015; 12: 263–274.

26. Kimura, M. Source and fate of organic-c in paddy field ecosystem. Proceedings of the 9th U.S.-Japan workshop on global change. Carbon cycle management in terrestrial ecosystems. October 9-11, Mita Conference Hall, Tokyo, Japan. 2001; 42.

27. Rees RM, Bingham IJ, Baddeley JA, Watson CA. The role of plants and land management in sequestering soil carbon in temperate arable and grassland ecosystems. Geoderma. 2005: 128:

30–15.

28. Hu R, Hatano R, Kusa K, Sawamoto T. Soil respiration and net ecosystem production in an onion field in central Hokkaido, Japan. Soil Sci. Plant Nutr. 2004; 50(1): 27–33.

29. MU Zhijian, Kimura, S.D.; Hatano, R. Estimation of global warming potential from upland cropping systems in central Hokkaido, Japan. Soil Sci. Plant Nutr. 2006; 52: 372–378.

30. Koizumi H, Usami Y, Satoh M. Carbon dynamics and budgets in three upland-double cropping systems in Japan. Agric. Ecosyst. Environ. 1993; 43: 235–244.

31. Koizumi H. Carbon dynamics and sequestration in two different cropping systems in Japan. Proceedings of the 9th U.S. Japan workshop on global change. Carbon cycle management in terrestrial ecosystems. October 9-11, Mita Conference Hall, Tokyo, Japan. 2001; p. 50.

32. Liping G, Erda L. Carbon sink in cropland soils and the emission of greenhouse gases from paddy soils: a review of work in China. Chemosphere. 2001; 3: 413–418.

33. Omura Y, Furumi S, Daigo M, Muramatsu K. Estimation of Net Primary Production in Paddy Fields of Japan using Satellite Data. ResearchGate. 2005.

34. Shinano T, Osaki M, Tadano T. Effect of nitrogen application on reconstruction of nitrogen compounds during the maturation stage in several field crops. Soil Sci. Plant Nutr. 1991; 37: 259–270.

35. Lamptey S, Li L.L, Xie JH. Impact of nitrogen fertilization on soil respiration and net ecosystem production in maize. Plant Soil Environ. 2018; 64(8); 353–360.

36. Awaya Y. NPP estimation of forest area using satellite data. Proceedings of the 9th U.S.-Japan workshop on global change. Carbon cycle management in terrestrial ecosystems. October 9-11, Mita Conference Hall, Tokyo, Japan. 2001; p. 59.

37. Witt C, Cassman KG, Olk DC, Biker U, Liboon SP, Samson MI, Ottow JCG. Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. Plant Soil. 2000; 225: 263–278.

38. Sanchis E, Ferrer M, Torres AG, Maria CL, Calvet S. Effect of Water and Straw Management Practices on Methane Emissions from Rice Fields: A Review Through a Meta-Analysis. Environmental Engineering Science. 2012; 29(12): 1053–1062. DOI: 10.1089/ees.2012.0006

39. Eusuf MK, Tokida T, Sugiyama S, Nakajima M, Sameshima R. Effect of rice straw on CH_4 emission in continuous and recent converted paddy field. J. Agric. Meteorol. 2011; 67: 185–192.

40. Tyagi L, Kumari B, Singh SN. Water management - A tool for methane mitigation from irrigated paddy fields. Sci. Total Environ. 2010; 408; 1085-1090.

41. Yan X, Yagi K, Akiyama H, Akimoto H. Statistical analysis of major variables controlling methane emission from rice fields. Global Change Biol. 2005; 11: 1131-1141.

42. Wang JY, Jia JX, Xiong ZQ, Khalil MAK, Xing GX. Water regime–nitrogen fertilizer–straw incorporation interaction: field study on nitrous oxide emissions from a rice agroecosystem in Nanjing, China. Agric Ecosyst Enviro. 2011; 141: 437–446.

43. Yao Z, Zhou Z, Zheng X, Xie B, Mei B, Wang R, Butterbach-Bahl K, Zhu J. Effects of organic matter incorporation on nitrous oxide emissions from rice-wheat rotation ecosystems in China. Plant Soil. 2010; 327: 315–330.

44. Zou JW, Huang Y, Jiang J, Zheng X, Sass R. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochem Cycles. 2005; 19: 1–.9 GB002401. GB2021, doi:10.1029.

45. Ma J, Ma E D, Xu H, Yagi K. Cai ZC. Wheat straw management affects CH4 and N2O emissions from rice fields. Soil Biol Biochem. 2009; 41: 1022–1028.

46. Abao EB, Bronson KF, Wassmann R, Singh U. Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rainfed conditions. Nutr. Cycle Agroecosyst. 2000; 58: 131–140.

47. Zheng X, Wang M, Wang Y. Shen, Jing L, Heyer J, Koegge M, Papen H, Jisheng J, Laotu L. Mitigation options for methane, nitrous oxide and nitric oxide emissions from agricultural ecosystems. Adv. Atmos. Sci. 2000; 17(1): 83–92.

48. Aulakh MS, Khera TS, Doran JW, Bronson KF. Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping system as affected by crop residues, fertilizer N and legume green manure. Biol. Fertil. Soils. 2001; 34: 375–389.

49. Chen B, Liu E, Tian Q, Yan C, Zhang Y. Soil nitrogen dynamics and crop residues. A review Agron. Sustain. Dev. 2014; 34: 429–442.

50. Chèneby D, Bru D, Pascault N, Maron PA, Ranjard L, Philippot L. Role of Plant Residues in Determining Temporal Patterns of the Activity, Size, and Structure of Nitrate Reducer Communities in Soil. Applied and Environmental Microbiology. 2010; p. 7136–7143

51. Granli T, Bøckman OC. Nitrous oxide from agriculture. Norw. J. Agric. Sci. Suppl. 1994; 12: 34–40.

52. Zheng XH, Wang MX, Wang YS, Shen RX, Gou J, Li J, Jin JS, Li LT. Impact of soil moisture on nitrous oxide emission from croplands: a case study on the rice-based agro-ecosystem in Southeast China. Chemosphere – Glob. Change Sci., 2000; 2: 207–224. doi:10.1016/S1465-9972 (99)00056-2.

53. Cai ZC, Laughlin JR, Stevens RJ. Nitrous oxide and dinitrogen emissions from soil under different water regimes and straw amendment. Chemosphere. 2001; 42: 113–121. doi:10.1016/S0045-6535(00)00116-8

54. Xu YC, Shen QR, Li ML, Dittert K, Sattelmacher B. Effect of soil water status and mulching on N2O and CH4 emission from lowland rice field in China. Biol. Fertil. Soils. 2004; 39: 215–217. doi:10.1007/s00374-003-0692-4

55. Zou JW, Huang Y, Jiang JY, Zheng H, Sass RL. A 3-year field measurement of methane and nitrous oxide emission from rice paddies in China: effects of water regime, crop residue, and fertilizer application. Glob. Biogeochem. Cycles. 2005; 19: GB 2021. doi:10.1029/2004GB002401

56. Hadi A, Inubushi K, Yagi K. Effect of water management on greenhouse gas emissions and microbial properties of paddy soils in Japan and Indonesia. Paddy Water Environ. 2010; 8: 319–324.

57. Zou J, Huang Y, Jiang J. A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochem. Cycles. 2005; 19: 1–9.

58. IPCC—Intergovernmental Panel on Climate Change. Climate Change 2001. The Scientific Basis. Contribution of working group I to the third assessment report of the IPCC. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosa D. Cambridge Univ. Press.

59. Robertson G.P, Paul EA, Harwood RR. Greenhouse gases in intensive agriculture: contributions of individual gases to the radiative forcing of the atmosphere. Science. 2000; 289: 1922–1925.

60. Six J, Ogle SM, Breidt FJ, Conant RT, Mosier AR, Paustian K. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biol. 2004; 10: 155–160.

61. Yu K, Patrick WHJr. Redox window with minimum global warming potential contribution from rice soils. Soil Sci. Soc. Am. J. 2004; 68: 2086–2091.

62. Wu X, Wang W, Xie X, Yin C, Hou H, Ya W, Wang G. Net global warming potential and greenhouse gas intensity as affected by different water management strategies in Chinese double rice-cropping systems. Scientific Reports, 2018; 8:779| DOI:10.1038/s41598-017-19110-2.

63. Naser H.M, Nagata O, Hatano R. Greenhouse gas fluxes and global warming potentials in crop fields on soil-dressed peatland in Hokkaido, Japan. Phyton. 2005; 45(4): 285–293.

64. Shang QY, Yang X, Gao C, Wu P, Liu J, Xu Y, Shen Q, Zou J, Gao S. Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. Global Change Biol. 2011; 17: 2196–2210.

65. Li C, Salas W, DeAngelo B, Rose S. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in china over the next twenty years. J. Environ. Qual. 2006; 35: 1554–1565.

66. Xiong Z, Liu Y, Wu Z, Zhang X, Liu P, Huang T. Differences in net global warming potential and greenhouse gas intensity between major rice-based cropping systems in China. Scientific Report. 2015; 2(5): 17774. doi: 10.1038/srep17774.

Table 1. Some physical and chemical characteristics of the investigated paddy field soils (initial soil at 0-10 cm depth).

Site[§]	Soil type[¶]	Soil pH	Particle size distribution (%)			Soil texture	Bulk density	Total-N	Total-C
		(H_2O)	Sand	Silt	Clay		(g cm^{-3})	(g kg^{-1})	(g kg^{-1})
D_1-M	SDP	5.38	28.8	47.1	24.2	SICL	0.96	3.86	57.8
D_2-M	SDP	5.32	29.9	46.9	23.1	SICL	0.87	3.03	43.5
D_3-S	SDP	5.45	50.9	33.5	15.6	CL	1.15	1.65	24.7

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). [¶] SDP, soil-dressed peat.

Table 2. Summary of management practices of the investigated paddy fields.

Site[§]	Field area	Dates of					Nitrogen fertilizer application	Straw leftover on field		
		Trans-planting	Multiple/single drainage		Final drainage for harvest	Harvest		Dry matter	C conc.	C amount
			1st drainage	2nd drainage						
	($10^4 m^2$)						(kg N ha^{-1})	(g m^{-2})	(%)	(g C m^{-2})
D_1-M	0.54	24-May	22-Jun.	25-Jul.	15-Aug.	15-Sep.	76	521	41.7	217
D_2-M	0.48	24-May	22-Jun.	25-Jul.	15-Aug.	15-Sep.	76	558	40.4	225
D_3-S	0.35	25-May	-	26-Jul.	15-Aug.	25-Sep.	36	751	39.2	295

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single).

Table 3. Seasonal greenhouse gas fluxes and their contribution to total annual gas fluxes from paddy-fallow cropping systems.

Site[§]	Gas fluxes									Proportion of contribution from G or F[†] to annual total emission		
	Rice growing season (G) (June to September)			Winter-fallow season (F) (October to April)			Annual total (m^{-2} yr^{-1})					
	R_m ^{NS}	CH_4 ^{NS}	N_2O *	R_m ^{NS}	CH_4**	N_2O**	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
	(g C m^{-2})	(g C m^{-2})	(g N m^{-2})	(g C m^{-2})	(g C m^{-2})	(g N m^{-2})	(g C)	(g C)	(g N)	(%)		
D_1-M	274±71.4	75.5±24.6	0.024±0.018b	223±53.8	-0.019±0.008c	0.067±0.016b	497	75.5	0.091	55.1 G	100 G	73.5 F
D_2-M	284±88.2	76.8±30.0	0.036±0.016a	235±55.6	0.039±0.015b	0.118±0.027a	519	76.8	0.154	54.7 G	100 G	76.6F
D_3-S	234±72.2	116±23.5	0.003±0.004c	188±44.9	0.119±0.029a	0.013±0.004c	422	116	0.016	55.5G	100 G	81.3 F

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). [†]G, rice growing season.
F, winter-fallow season.
Values in a column followed by a common letter are not significantly different at *$p < 0.05$ & **$p < 0.01$. NS, non significant.

Table 4. Rice variety, net primary production (NPP) and grain yield of rice with their C content.

Site[§]	Rice variety	Grain yield			Net primary production (whole plant[†])		
		Dry matter (g m^{-2})	C content (%)	C amount (g C m^{-2})	Dry matter (g m^{-2})	C content (%)	C amount (g C m^{-2})
D_1-M	Kirara 397	627±75.7	42.4±0.25	266±32.3	1182±138	42.3±0.33	499±57.7
D_2-M	Nanatsuboshi	710±42.7	42.0±0.22	298±17.4	1278±66.8	41.3±0.08	529±27.6
D_3-S	Kirara 397	713±10.3	41.6±0.22	297±5.15	1306±4.92	40.6±0.36	530±2.18

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). [†] Whole rice plant (total biomass) includes grain, straw and stubble with roots.

Table 5. Annual C sequestration from paddy-fallow cropping systems.

Site[§]	NPP (whole plant)	Grain yield	Annual emission		C sequestration[†]
			R_m	CH_4	
	(g C m^{-2})	(g C m^{-2})	(g C m^{-2} yr^{-1})	(g C m^{-2} yr^{-1})	(g C m^{-2} yr^{-1})
D_1-M	499	266	497	75.5	-339
D_2-M	529	298	519	76.8	-365
D_3-S	530	297	422	116	-305

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single).
[†]C sequestration = NPP– (R_m + CH_4 + grain harvest + straw harvest)
Note: all harvested straw leftover on three fields, i.e., straw harvest = 0. Negative values of C sequestration indicate net CO_2 emission from soils.

Table 6. Seasonal CS or C loss and their contribution to annual CS or C loss.

Site[§]	CS in growing season[‡] (g C m^{-2} season^{-1})	CS in winter-fallow season (g C m^{-2} season^{-1})	CS yr^{-1} (g C m^{-2} yr^{-1})	Proportion of contribution to annual C loss from G or F[†] (%)
D_1-M	-116	-223	-339	66 from F
D_2-M	-130	-235	-365	64 from F
D_3-S	-116	-188	-305	62 from F

[§] D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single). [†]G, rice growing season. F, winter-fallow season. [‡]C sequestration (CS growing season^{-1}) = NPP – (R_m + CH_4 + grain harvest). C sequestration (CS winter-fallow^{-1}) = – (R_m + CH_4 + straw harvest). Note: all harvested straw leftover on four fields, i.e., straw harvest = 0. Negative values of C sequestration indicate net CO_2 emission from soils.

Table 7. Seasonal GWP (g CO_2 equivalent m^{-2}) of CO_2, CH_4 and N_2O and their contribution to annual GWP.

Site§	GWP during rice growing season			GWP during winter-fallow season			Annual GWP of individual GHG gas basis			Proportion of contribution from G or F† to annual GWP of respective gas (%)		
	CO_2‡	CH_4	N_2O	CO_2‡	CH_4	N_2O	CO_2‡	CH_4	N_2O	CO_2	CH_4	N_2O
D_1-M	149	2819	10.2	817	-0.70	27.7	967	2818	38.0	85 F	100 G	73 F
D_2-M	196	2867	15.1	861	1.46	49.2	1057	2868	64.3	81F	100 G	77 F
D_3-S	3.52	4312	1.36	689	4.45	5.23	693	4317	6.59	99 F	100 G	79 F

§ D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single).
‡ GWP of CO_2 = – (CS + CH_4 flux) × (44/12). †G, rice growing season. F, winter-fallow season.

Table 8. Proportion of contribution from seasonal net GWP and annual GWP of individual GHG to annual net GWP.

Site§	Net GWP (g CO_2 eq. m^{-2} $season^{-1}$)		Proportion of contribution from G or F† to annual net GWP	(g CO_2 eq. m^{-2} yr^{-1}) Annual GWP of individual GHG basis			Annual net GWP	Proportion of contribution from individual GHG basis GWP to net GWP (%)		
	growing season	winter-fallow season	(%)	CO_2‡	CH_4	N_2O		CO_2‡	CH_4	N_2O
D_1-M	2978	844	78 from G	967	2818	38.0	3823	25.3	73.7	0.99
D_2-M	3078	911	77 from G	1057	2868	64.3	3990	26.5	71.9	1.61
D_3-S	4317	699	86 from G	693	4317	6.59	5016	13.8	86.1	0.13

§ D_1-M (drainage-multiple); D_2-M (drainage-multiple); D_3-S (drainage-single).
‡ GWP of CO_2 = – (CS + CH_4 flux) × (44/12). †G, rice rice growing season; F, winter-fallow season.

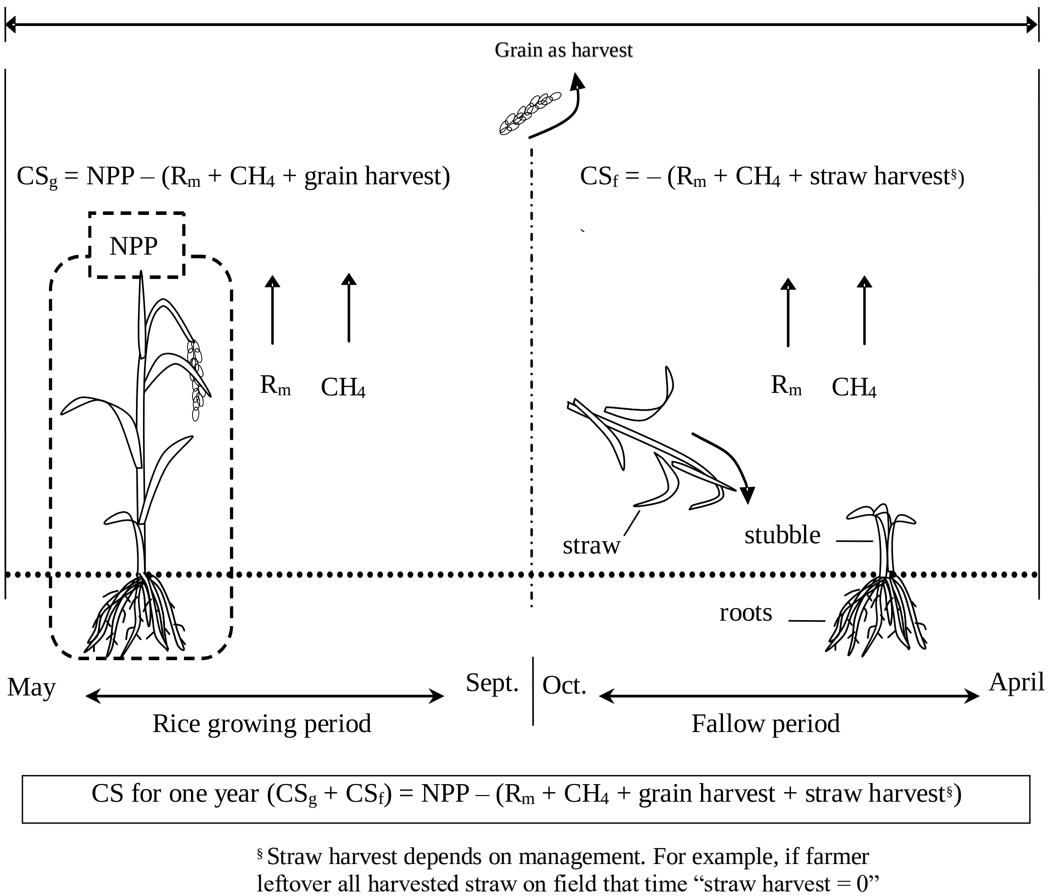

Fig. 1. Schematic diagram of carbon sequestration (CS) estimation procedure.

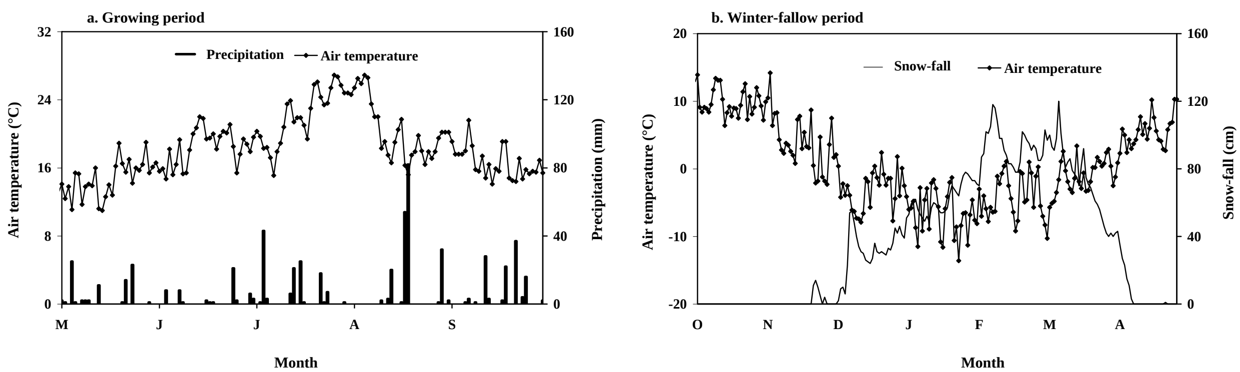

Fig. 2 a, b. Climatic conditions of investigated area during rice growing and winter-fallow period.