Carbon Sequestration and Contribution of CO₂, CH₄ and N₂O 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 CO₂, CH₄ and N₂O fluxes to a global warming potential (GWP). CH₄ and N₂O fluxes were measured by placing the chamber over the rice plants covering four hills and CO₂ fluxes from rice plants root free space in paddy fields were taken as an indicator of soil microbial respiration (Rₘ) using the closed chamber method. Annual cumulative Rₘ 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 CH₄ 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 N₂O emission ranged from 0.091 to 0.154 g N m⁻² yr⁻¹ and 73.5 to 81.3% of the positive annual N₂O emission observed during the winter-fallow season. Soil C sequestration was estimated as the difference between net primary production (NPP) and C loss through Rₘ, CH₄ 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 CO₂ equivalent m⁻² yr⁻¹. Annual GWP\textsubscript{CH₄} accounted for 71.9 to 86.1% of the annual net GWP predominantly from the rice growing period. These results indicate that CH₄ 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 (CO₂), methane (CH₄), and nitrous oxide (N₂O) 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 CH₄ fluxes [5]. Lower CH₄ fluxes due to water drainage may increase N₂O fluxes [6]. Studies have shown that a large amount of GHGs are released from paddy fields and that a substantial quantity of CO₂ 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 CO₂ and CH₄ between rice paddies and the atmosphere are controlled by several biological and physical processes. CO₂ exchange in rice paddies is driven by photosynthesis and autotrophic (plant) and heterotrophic (mainly microbial) respiration [9]. Plant photosynthesis leads to uptake of CO₂ from both the atmosphere and from respired CO₂ emitted by the soil and floodwater. CH₄ is released to the atmosphere by ebullition, diffusion
and by transport through rice plant aerenchyma tissue [10]. More than 90% of the total CH₄ 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 CH₄ and N₂O but not CO₂ when estimating GWP in paddy fields, because both respiration and photosynthesis activities contributed to CO₂ 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 CO₂ 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 CH₄ and N₂O emissions from paddy soils had been estimated together or separately by numerous researchers [6,15,16]. With regard to the integrated greenhouse effect in CO₂-equivalent of three gases (CO₂, CH₄ and N₂O), 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 (Rₘ) 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$_2$O 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 D1-M and D2-M, and single drainage (mid-season) in middle of growing
season was done in D3-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 D3-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 D1-M, D2-M and D3-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. CH₄ and N₂O 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\(_2\)O 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 °C, respectively. Calibration was performed using N\(_2\)O 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

\(\text{CO}_2\) 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 \(\times\) 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 \(\text{CH}_4\) and \(\text{N}_2\text{O}\) 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\textsuperscript{®} bag through a silicon tube attached to the top of the chamber. \(R_m\) (\(\text{CO}_2\)) 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:
\[ F \text{ (mg C m}^{-2} \text{ h}^{-1}) = \rho \times V / A \times \Delta c / \Delta t \times 273/T \times \alpha \quad (1) \]

where, \( F \) is the gas flux; \( \rho \) is the density of gas at the standard condition (\( R_m \) as CO\(_2\) = 1.96 \times 10^6 \text{ mg m}^{-3}, \text{CH}_4 = 0.716 \times 10^6 \text{ mg m}^{-3}, \) and N\(_2\O = 1.97 \times 10^6 \text{ mg m}^{-3} \); \( V \) (m\(^3\)) and \( A \) (m\(^2\)) are the volume and bottom area of the chamber, respectively; \( \Delta c / \Delta t \) (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 \( \alpha \) is the conversion factor for gas (CO\(_2\) = 12/44, \text{CH}_4 = 12/16 and N\(_2\O = 28/44 \)). 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:

\[ \text{Cumulative gas emission} = \Sigma (R_i \times D_i) \quad (2) \]

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 \( \rho_b \) (g cm\(^{-3}\)) was obtained by \( \rho_b\) = 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-m² 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-m² 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):

\[
CS_g = NPP - (R_m + CH_4 \text{ emission} + \text{grain harvest}) \quad (3)
\]

\[
CS_f = -(R_m + CH_4 \text{ emission} + \text{straw harvest}) \quad (4)
\]
For one year:

\[ CS_g + CS_f = NPP - (R_m + CH_4 \text{ emission} + \text{grain harvest} + \text{straw harvest}) \]  

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-m² quadrates 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 (\( g \ CO_2 \text{ equivalent m}^{-2} \text{ season}^{-1} \)) 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:

\[ \text{Net GWP} = CO_2 \text{ GWP} + CH_4 \text{ GWP} + N_2O \text{ GWP} \]  

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

\[ CH_4 \text{ GWP} = CH_4 \ (g \ CH_4-C \text{ m}^{-2} \text{ season}^{-1}) \times (16/12) \times 28; \text{ and} \]

\[ N_2O \text{ GWP} = N_2O \ (g \ N_2O-N \text{ m}^{-2} \text{ season}^{-1}) \times (44/28) \times 265. \]

### 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: 0.8 to 14.2°C). During the snowy period (late November–late April) the average air temperature was -2.2°C (range: -13.6 to 10.2°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, D1-M, D2-M and D3-S was ranged from 188 to 235 during winter-fallow period. The annual cumulative R_m of D2-M field showed the highest rate (519) and the lowest from D3-S D3-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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O 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$_2$O emissions during the rice-growing season [42,43]. The observed decreases in N$_2$O 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$_2$O emissions [44,45]. In fact there is some evidence that N$_2$O 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$_2$O diffusion in soil is severely hindered by the water layer. It has been generally thought that the emission rate of N$_2$O from rice paddy field to the atmosphere was very low. Generally, low N$_2$O fluxes are found during flooded periods, whereas high N$_2$O 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 CO₂, CH₄ and N₂O

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 CH₄ and N₂O emissions in rice paddies under various agricultural practices and not CO₂ emission in their estimation. Moreover, Xiao et al. [7] estimated net GWP (g CO₂ equivalent m² yr⁻¹) in paddy field where the GWP of N₂O and CH₄ 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 GWP₃CO₂ estimation. In our study for computation of GWP₃CO₂ 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 et al. [56] reported that net GWP from intermittently drained paddy fields in South Kalimantan, Indonesia was 2091 (g CO₂ equivalent m⁻² growing season⁻¹). Moreover, Wu et al. [62] reported that the net GWPs was 890 g CO₂-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 CO₂ equivalent m⁻²-late March to mid December), where CO₂ 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 CH₄ emission from the studied fields. The fields with positive net GWP in this study showed annual GWPₗ₄ accounted for 71.9 to 86.1% of the annual net GWP. In seasonal aspect, GWPₗ₄ contributed 100% to the annual net GWP mainly from the rice growing period. On the other hand, GWP₃ and GWP₅ contributed 81 to 99% and 73 to 79%, respectively from winter-fallow season. Methane has been reported to account for 95% of total CO₂-equivalent emissions from paddy fields based on GWP [63]. Xiao et al. [7] reported that the annual net GWP (g CO₂ equivalent m⁻²) in paddy field was estimated to be 640 to 1124, and CH₄ emission contributed to 90 to 99% of the net GWP. Those results indicated that CH₄ dominated the rice paddy’s positive net GWP, whereas CO₂
dominated for the upland crops. The proportion of contribution (%) from individual GHG basis GWP to net GWP of CO₂, CH₄, and N₂O were 13.8 to 26.5, 71.9 to 86.1 and 0.13 to 1.61, respectively. This indicates that CH₄ 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 CH₄ emissions, consistent with the findings of previous studies [64,65,66].

5. Conclusion

Paddy-fallow cropping systems could be sources of atmospheric CO₂, CH₄ and N₂O. 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 (CO₂-C and CH₄-C). The annual GWPₐ₄ 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 CH₄ 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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Conflicts of Interest: The authors declare no conflict of interest.


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


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

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil type</th>
<th>Soil pH (H₂O)</th>
<th>Particle size distribution (%)</th>
<th>Soil texture</th>
<th>Bulk density (g cm⁻³)</th>
<th>Total-N (g kg⁻¹)</th>
<th>Total-C (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₁-M</td>
<td>SDP</td>
<td>5.38</td>
<td>28.8  47.1  24.2</td>
<td>SICL</td>
<td>0.96</td>
<td>3.86</td>
<td>57.8</td>
</tr>
<tr>
<td>D₂-M</td>
<td>SDP</td>
<td>5.32</td>
<td>29.9  46.9  23.1</td>
<td>SICL</td>
<td>0.87</td>
<td>3.03</td>
<td>43.5</td>
</tr>
<tr>
<td>D₃-S</td>
<td>SDP</td>
<td>5.45</td>
<td>50.9  33.5  15.6</td>
<td>CL</td>
<td>1.15</td>
<td>1.65</td>
<td>24.7</td>
</tr>
</tbody>
</table>

† D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single). ‡ SDP, soil-dressed peat.

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

<table>
<thead>
<tr>
<th>Site</th>
<th>Field area (10⁴m²)</th>
<th>Transplanting</th>
<th>Dates of 1st drainage</th>
<th>Final drainage for harvest</th>
<th>Harvest</th>
<th>Nitrogen fertilizer application (kg N ha⁻¹)</th>
<th>Dry matter (g m⁻²)</th>
<th>C conc. (%)</th>
<th>C amount (g C m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D₁-M</td>
<td>0.54</td>
<td>24-May</td>
<td>22-Jun.</td>
<td>15-Aug.</td>
<td>15-Sep.</td>
<td>76</td>
<td>521</td>
<td>41.7</td>
<td>217</td>
</tr>
<tr>
<td>D₂-M</td>
<td>0.48</td>
<td>24-May</td>
<td>22-Jun.</td>
<td>15-Aug.</td>
<td>15-Sep.</td>
<td>76</td>
<td>558</td>
<td>40.4</td>
<td>225</td>
</tr>
<tr>
<td>D₃-S</td>
<td>0.35</td>
<td>25-May</td>
<td>-</td>
<td>15-Aug.</td>
<td>25-Sep.</td>
<td>36</td>
<td>751</td>
<td>39.2</td>
<td>295</td>
</tr>
</tbody>
</table>

† D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single).

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

<table>
<thead>
<tr>
<th>Site</th>
<th>Rice growing season (G) (June to September)</th>
<th>Winter-fallow season (F) (October to April)</th>
<th>Annual total (m³ yr⁻¹)</th>
<th>Proportion of contribution from G or F to annual total emission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rₙm NS (g C m⁻²)</td>
<td>CH₄ NS (g C m⁻²)</td>
<td>N₂O NS (g N m⁻²)</td>
<td>CO₂ (g C)</td>
</tr>
<tr>
<td>D₁-M</td>
<td>274±71.4</td>
<td>75.5±24.6</td>
<td>0.024±0.018b</td>
<td>223±53.8</td>
</tr>
<tr>
<td>D₂-M</td>
<td>284±88.2</td>
<td>76.8±30.0</td>
<td>0.036±0.016a</td>
<td>235±55.6</td>
</tr>
<tr>
<td>D₃-S</td>
<td>234±72.2</td>
<td>116±23.5</td>
<td>0.003±0.004c</td>
<td>188±44.9</td>
</tr>
</tbody>
</table>

† D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-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.

<table>
<thead>
<tr>
<th>Site</th>
<th>Rice variety</th>
<th>Dry matter (g m(^{-2}))</th>
<th>C content (%)</th>
<th>C amount (g C m(^{-2}))</th>
<th>Dry matter (g m(^{-2}))</th>
<th>C content (%)</th>
<th>C amount (g C m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(_1)-M</td>
<td>Kirara 397</td>
<td>627±75.7</td>
<td>42.4±0.25</td>
<td>266±32.3</td>
<td>1182±138</td>
<td>42.3±0.33</td>
<td>499±57.7</td>
</tr>
<tr>
<td>D(_2)-M</td>
<td>Nanatsuboshi</td>
<td>710±42.7</td>
<td>42.0±0.22</td>
<td>298±17.4</td>
<td>1278±66.8</td>
<td>41.3±0.08</td>
<td>529±27.6</td>
</tr>
<tr>
<td>D(_3)-S</td>
<td>Kirara 397</td>
<td>713±10.3</td>
<td>41.6±0.22</td>
<td>297±5.15</td>
<td>1306±4.92</td>
<td>40.6±0.36</td>
<td>530±2.18</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Site</th>
<th>NPP (whole plant) (g C m(^{-2}))</th>
<th>Grain yield (g C m(^{-2}))</th>
<th>Annual emission</th>
<th>R(_m) (g C m(^{-2}) yr(^{-1}))</th>
<th>CH(_4) (g C m(^{-2}) yr(^{-1}))</th>
<th>C sequestration(^{†}) (g C m(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(_1)-M</td>
<td>499</td>
<td>266</td>
<td>497</td>
<td>75.5</td>
<td>-339</td>
<td></td>
</tr>
<tr>
<td>D(_2)-M</td>
<td>529</td>
<td>298</td>
<td>519</td>
<td>76.8</td>
<td>-365</td>
<td></td>
</tr>
<tr>
<td>D(_3)-S</td>
<td>530</td>
<td>297</td>
<td>422</td>
<td>116</td>
<td>-305</td>
<td></td>
</tr>
</tbody>
</table>

\(^{†}\) D\(_1\)-M (drainage-multiple); D\(_2\)-M (drainage-multiple); D\(_3\)-S (drainage-single).

C sequestration = NPP \(\text{–} (R_m + CH_4 + \text{grain harvest} + \text{straw harvest})\) 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.

<table>
<thead>
<tr>
<th>Site</th>
<th>CS in growing season(^{‡}) (g C m(^{-2}) season(^{-1}))</th>
<th>CS in winter-fallow season (g C m(^{-2}) season(^{-1}))</th>
<th>CS yr(^{-1}) (g C m(^{-2}) yr(^{-1}))</th>
<th>Proportion of contribution to annual C loss from G or F(^{†}) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D(_1)-M</td>
<td>-116</td>
<td>-223</td>
<td>-339</td>
<td>66 from F</td>
</tr>
<tr>
<td>D(_2)-M</td>
<td>-130</td>
<td>-235</td>
<td>-365</td>
<td>64 from F</td>
</tr>
<tr>
<td>D(_3)-S</td>
<td>-116</td>
<td>-188</td>
<td>-305</td>
<td>62 from F</td>
</tr>
</tbody>
</table>

\(^{‡}\) D\(_1\)-M (drainage-multiple); D\(_2\)-M (drainage-multiple); D\(_3\)-S (drainage-single). \(^{†}\) C sequestration (CS growing season) = NPP – (R\(_m\) + CH\(_4\) + grain harvest). C sequestration (CS winter-fallow) = – (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 CO₂ equivalent m⁻²) of CO₂, CH₄ and N₂O and their contribution to annual GWP.

<table>
<thead>
<tr>
<th>Site</th>
<th>GWP during rice growing season</th>
<th>GWP during winter-fallow season</th>
<th>Annual GWP of individual GHG gas basis</th>
<th>Proportion of contribution from G or F¹ to annual GWP of respective gas (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂‡</td>
<td>CH₄</td>
<td>N₂O</td>
<td>CO₂‡</td>
</tr>
<tr>
<td>D₁-M</td>
<td>149</td>
<td>2819</td>
<td>10.2</td>
<td>817</td>
</tr>
<tr>
<td>D₂-M</td>
<td>196</td>
<td>2867</td>
<td>15.1</td>
<td>861</td>
</tr>
<tr>
<td>D₃-S</td>
<td>3.52</td>
<td>4312</td>
<td>1.36</td>
<td>689</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Site</th>
<th>Net GWP (g CO₂ eq. m⁻² season⁻¹)</th>
<th>Proportion of contribution from G or F¹ to annual net GWP</th>
<th>(g CO₂ eq. m⁻² yr⁻¹)</th>
<th>Annual GWP of individual GHG basis</th>
<th>Annual net GWP</th>
<th>Proportion of contribution from individual GHG basis GWP to net GWP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Proportion of contributio</td>
<td>Annual GWP</td>
<td>Annual</td>
<td>Proportion of contributio</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>n from G or F¹ to</td>
<td>GWP</td>
<td>net GWP</td>
<td>from individual</td>
<td>of GWP to net GWP (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>annual net GWP</td>
<td>GWP</td>
<td>basis</td>
<td>GWP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(%)</td>
<td>CO₂‡</td>
<td>CH₄</td>
<td>N₂O</td>
<td>CO₂‡</td>
</tr>
<tr>
<td>D₁-M</td>
<td>2978</td>
<td>844</td>
<td>78 from G</td>
<td>967</td>
<td>2818</td>
<td>38.0</td>
</tr>
<tr>
<td>D₂-M</td>
<td>3078</td>
<td>911</td>
<td>77 from G</td>
<td>1057</td>
<td>2868</td>
<td>64.3</td>
</tr>
<tr>
<td>D₃-S</td>
<td>4317</td>
<td>699</td>
<td>86 from G</td>
<td>693</td>
<td>4317</td>
<td>6.59</td>
</tr>
</tbody>
</table>

¹ D₁-M (drainage-multiple); D₂-M (drainage-multiple); D₃-S (drainage-single).
² GWP of CO₂ = – (CS + CH₄ flux) × (44/12).
³ G, rice growing season; F, winter-fallow season.
Fig. 1. Schematic diagram of carbon sequestration (CS) estimation procedure.

\[ CS_g = \text{NPP} - (R_m + \text{CH}_4 + \text{grain harvest}) \]

\[ CS_f = -(R_m + \text{CH}_4 + \text{straw harvest}) \]

Straw harvest depends on management. For example, if farmer leftover all harvested straw on field that time “straw harvest = 0”

CS for one year \((CS_g + CS_f) = \text{NPP} - (R_m + \text{CH}_4 + \text{grain harvest} + \text{straw harvest})\)

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