

## Article

# Effects of the Autumn Incorporation of Rice Straw and Application of Lime Nitrogen on Methane and Nitrous Oxide Emissions and Rice Growth of a High-Yielding Paddy Field in a Cool-Temperate Region in Japan

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**Abstract:** The effects of autumn plowing and lime nitrogen application on rice straw decomposition, CH<sub>4</sub> and N<sub>2</sub>O emission and rice growth in the following year in a high-yielding rice cultivated paddy field were evaluated for two years. The experimental plots were set up, combining different times of rice straw (750 g m<sup>-2</sup>) incorporation into the soil by plowing (autumn or the following spring), with and without lime nitrogen application in autumn (5 g-N m<sup>-2</sup>). Autumn plowing promoted the decomposition of rice straw, but the application of lime nitrogen did not show a consistent trend. The soil pH was high (7.3) at the studied site, and the alkaline effect of lime nitrogen may not have been significant. As with straw decomposition, CH<sub>4</sub> emissions were suppressed by autumn plowing, and no effect from the lime nitrogen application was observed. It was also suggested that the straw decomposition period may be shorter and the CH<sub>4</sub> emissions may be higher in high-yielding cultivars that require a longer ripening period than in normal cultivars. The effect of both treatments on N<sub>2</sub>O emission was not clear. Both the autumn plowing of rice straw and lime nitrogen application were effective in promoting rice growth and increasing rice yield.

**Keywords:** high-yielding variety; lime nitrogen; litter bag method; methane; nitrous oxide; shallow plowing



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## 1. Introduction

In recent years, the demand for rice, a staple food in Japan, has been decreasing by 80,000 tons annually [1]. On the other hand, the cultivation area of rice for new sources of demand, such as rice flour, feed, etc., increased by about 120,000 ha from 2008 to 2018. This is because methods promoting the effective utilization of paddy fields through the cultivation of rice for new sources of demand have been recommended in order to improve Japan's food self-sufficiency. Since low-cost paddy rice cultivation is important for meeting the new demands of rice cultivation, high-yielding varieties are mainly being adopted.

In Japan, rice cultivation has been mechanized since the 1960s, and shredded rice straw is spread on the field when paddy rice is harvested by combine harvesters. In cool-temperate regions, such as northern Japan, the aerobic decomposition of rice straw sprayed on paddy fields is often inadequate by the following spring. When insufficiently decomposed rice straw is plowed into the soil in the following spring, and it rapidly decomposes with the rise in soil temperature after flooding, the result is an extreme reduction of soil (which becomes anaerobic). The reduction of soil promotes the production of organic acids and hydrogen sulfides which inhibit the initial growth of rice plants, and increase the emissions of methane (CH<sub>4</sub>), a potent greenhouse gas (GHG). Anaerobic methanogens use the cellulose and hemicellulose in rice straw as a substrate for methane

production. In general, as the yield of paddy rice increases, the amount of rice straw spread on the field also increases. Therefore, the problem caused by undecomposed rice straw is likely to be more serious when high-yielding varieties are grown [2].

Measures to reduce CH<sub>4</sub> emissions from paddy fields include the suppression of soil reduction through water management, such as mid-season drainage [3,4], and the promotion of rice straw decomposition through plowing in autumn and the application of lime nitrogen. It has been reported that plowing rice straw into the soil in autumn after the rice harvest promotes straw decomposition until spring and reduces CH<sub>4</sub> emissions in the following year [5]. The application of lime nitrogen has the effect of lowering the C/N ratio of rice straw and facilitating its decomposition. In addition, calcium cyanamide, the main component of lime nitrogen, produces dicyandiamide, which has an inhibitory effect on nitrification during the decomposition process. Compared to nitrogen derived from chemical fertilizers, such as ammonium sulfate, nitrogen derived from lime nitrogen is difficult to dissolve and tends to remain in the soil. Therefore, it can be expected to have a more long-term effect on promoting rice straw decomposition than nitrogen materials, such as ammonium sulfate (details on lime nitrogen can be found in [6]). There have been many reports on the reduction of methane emissions by the application of soil amendments to paddy fields, such as biochar [7,8] and steel slag containing iron and silica [9–12]. However, the effect of the application of materials intended to promote rice straw decomposition on CH<sub>4</sub> emissions from rice paddy fields has not been fully clarified.

The Tohoku region, located in northern Japan, is a major rice-producing area, containing 25% of the paddy fields in Japan. Compared to its area, the amount of CH<sub>4</sub> emission from rice paddies in the Tohoku region is estimated to be as large as 54% of Japan's total emissions [13]. It has been pointed out that this is due to the cool climate slowing the decomposition of organic matter in fallow season, and relatively lower drainage, resulting in enhanced CH<sub>4</sub> production in the rice growing season. In particular, the western part of the Tohoku region has problems associated with weather condition during the fallow season. One of the problems with plowing rice straw into the soil in autumn in this region is the unstable weather conditions after harvest and frequent rainfall. In the fields with plowing in autumn, the fields before spring tillage may have poor drainage conditions, which may interfere with paddy rice cultivation. Therefore, in this region, rice straw is often plowed in the following spring without plowing in autumn. However, if rice straw is plowed in the following spring, there is a high possibility that insufficient decomposition will cause the aforementioned inhibition of early rice growth and increased CH<sub>4</sub> emissions. It was reported that shallow tillage during autumn plowing accelerated the decomposition of rice straw without causing problems, such as poor drainage, and reduced CH<sub>4</sub> emissions [14]. In addition, as a method to promote rice straw decomposition when autumn plowing is not feasible, the technique of applying lime nitrogen to the field after harvest in autumn and plowing in the following spring may be effective. For these reasons, it is necessary to verify the effect of the shallow tillage of rice straw and the application of lime nitrogen in autumn on promoting straw decomposition.

In general, CH<sub>4</sub> emissions from rice paddies is a trade-off with nitrous oxide (N<sub>2</sub>O) emissions. It has been reported that measures to reduce CH<sub>4</sub> emissions, such as straw plowing by shallow tillage in autumn [14] and mid-season drainage [15], increase N<sub>2</sub>O emissions. Therefore, it is necessary to evaluate the effect of rice straw decomposition enhancement measures on N<sub>2</sub>O emissions as well as CH<sub>4</sub> emissions.

Therefore, the objective of this study was to examine the effects of autumn plowing and lime nitrogen application on rice straw decomposition, CH<sub>4</sub> and N<sub>2</sub>O emissions, and rice growth in the following year in a field growing a high-yielding rice variety.

## 2. Materials and Methods

### 2.1. Field Experiment

#### 2.1.1. Experimental Field, Setup and Cultivation

The field experiment was conducted at a continuous rice paddy field in the Field Education and Research Center of Akita Prefectural University in the Akita Prefecture (40°00' N, 139°57' E). The soil type is Gley lowland soil (Eutric Fluvisols). The main chemical properties of the studied soil are shown in Table 1. The experiment was conducted for two years, autumn 2016–autumn 2017 (2017 experiment) and autumn 2017–autumn 2018 (2018 experiment).

**Table 1.** Main chemical properties of the studied soil (0–10 cm).

Ph (H <sub>2</sub> O)	Total-C (g kg <sup>-1</sup> )	Total-N (g kg <sup>-1</sup> )	C/N Ratio	Available N <sup>†</sup> (mg-N kg <sup>-1</sup> )	Available P <sup>‡</sup> (mg-P <sub>2</sub> O <sub>5</sub> kg <sup>-1</sup> )
7.30	30.1	3.2	9.3	200	175
CEC (cmol <sub>C</sub> kg <sup>-1</sup> )	Exchangeable cation (cmol <sub>C</sub> kg <sup>-1</sup> )				Free ferric iron <sup>§</sup> (g-Fe <sub>2</sub> O <sub>3</sub> kg <sup>-1</sup> )
	Na	K	Ca	Mg	
45.6	0.89	1.19	45.6	4.88	16.7

<sup>†</sup> Ammonium–nitrogen (N) for 4-week incubation of air-dried soil under flooded conditions at 30 °C. <sup>‡</sup> Truog–phosphorus (P). <sup>§</sup> Determined by the sodium citrate–dithionite method. C, carbon; Ca, calcium; CEC, cation exchange capacity; K, potassium; Mg, magnesium; N, nitrogen; Na, sodium.

Granular lime nitrogen (Denka Co., Ltd., Tokyo, Japan) was used for the experiment. The nitrogen and alkali contents of the lime nitrogen were 20% and 55%, respectively. The rice (*Oryza sativa* L.) used in the experiment was the high-yielding variety Akita63. Akita63 is a large grain variety with a 1000-kernel weight of 30 g, which is larger than the staple food rice variety Akitakomachi (22–23 g). The average yield of Akita63 is about 1.5 times higher than that of Akitakomachi [16,17].

The experiment was conducted in paddy fields after rice cultivation in the previous year, using a combination of rice straw plowing time (autumn and the following spring) and lime nitrogen (no application or application) (4 treatment × 3 replications = 12 plots). The area of each plot was 34.5 m<sup>2</sup>.

A summary of treatment and an outline of the management and cultivation of the experimental field are shown in Tables 2 and 3, respectively. During the setting up of experimental plots (2017 experiment: 5 October 2016; 2018 experiment: 27 October 2017), rice straw (Akitakomachi in 2016 and Akita63 in 2017) shredded to 5 cm in length was sprayed over the entire field after harvest at 750 g m<sup>-2</sup> (Figure S1), and lime nitrogen was applied at 5 g-N m<sup>-2</sup> (25 g m<sup>-2</sup>) only in the treatment application. The amount of rice straw applied in this study was set based on the target yield of 720 g m<sup>-2</sup> for the high-yielding variety Akita63 [18], taking into account the ratio of grain to straw. The amount of lime nitrogen applied was calculated by multiplying the recommended amount for Akitakomachi (20 g m<sup>-2</sup>) by 1.25, since the target yield of Akita63 (720 g m<sup>-2</sup>) is about 1.25 times higher than that of Akitakomachi (570 g m<sup>-2</sup>). The autumn plowing plots were plowed at a depth of 5 cm and sprayed rice straw was plowed into the soil at that time (Figure S2). In the spring plowing plots, sprayed rice straw was not plowed into the soil but remained on the soil surface. A net was placed over the field to prevent straw from being blown away by the wind. In addition, corrugated plates were installed on the boundary line between the autumn and spring plowing plots to prevent water movement between the plots. During the fallow season, the fields are non-irrigated, but there is a lot of precipitation and the fields are in a wet condition. Usually, there is snowfall in January and February.

**Table 2.** Summary of each treatment.

Timing	Event	Treatment			
		NA-S	LN-S	NA-A	LN-A
Autumn (Previous year)	Rice straw application	○	○	○	○
	Lime nitrogen application	-	○	-	○
	Plowing	-	-	○	○
Spring	Basal fertilizer application	○	○	○	○
	Plowing	○	○	○	○

○, conducted; -, not conducted. Other than the above, the cultivation managements were the same for all treatments as described in Table 3. A, autumn; LN, lime nitrogen; NA, no application; S, spring.

**Table 3.** Outline of field management and cultivation.

Event	Date		Remarks
	2017	2018	
Previous year's cultivar	Akitakomachi	Akita63	In both years, cultivation by paddling and transplantation
Setup of experimental plots	5 October 2016	27 October 2017	750 g m <sup>-2</sup> of rice straw were scattered to all plots (Akitakomachi in autumn 2016, Akita63 in autumn 2017). 25 g m <sup>-2</sup> (5 g-N m <sup>-2</sup> ) of lime nitrogen were applied to the application plots. Autumn plowing plots were tilled about 5 cm with rotary, and spring plowing plots were not tilled
Basal fertilizer application	12 April 2017	13 April 2018	N, P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O: 5 g m <sup>-2</sup> , respectively (Compound chemical fertilizer)
Plowing	14 April	19 April	
Submerging	10 May	2 May	
Paddling	20 May	11 May	
Transplantation	25 May	16 May	20.6~21.7 hills m <sup>-2</sup>
Fertilizer top-dressing	4 July, 1 August	14 June, 19 July, 1 August	[2017] 2, 1.5 g-N m <sup>-2</sup> , respectively (Ammonium sulfate) [2018] 3, 1, 1 g-N m <sup>-2</sup> , respectively (Ammonium sulfate)
Mid-season drainage	10–19 July	Not conducted	
Final drainage	1 August	30 Jul	
(Heading period)	21 August	16 August	
Harvesting	19 October	15 October	

### 2.1.2. Measurement of Rice Straw Decomposition Rate

Paddy rice (Akitakomachi in 2016 and Akita63 in 2017) was harvested at a height of 5 cm above the ground's surface, assuming rice straw was spread by combine harvesting. The straw was cut at 30 cm from the base of the plant, the leaf blade was removed, and the straw was shredded into 5 cm-long pieces for the decomposition experiment. Ten grams of shredded rice straw were placed in a bag made of 20 cm × 20 cm non-woven fabric, and 0.33 g of lime nitrogen was added to the bag in the lime nitrogen treatment (calculated using rice straw:lime nitrogen = 750 g:25 g). The non-woven fabric was closed with a sealer after adding the rice straw and lime nitrogen, and was used as a bag for the decomposition experiment.

The rice straw bags were placed in the experimental plots after the application of rice straw and lime nitrogen and autumn plowing (2017 experiment: 12 October 2016; 2018 experiment: 1 November 2017). Following the design of the experimental plots in this study, the decomposition treatments were designed according to the combination of straw plowing time (autumn and the following spring) and lime nitrogen (no application or application). The rice straw bags were buried at a depth of 5 cm in the autumn plowing treatment and placed on the soil surface in the spring plowing treatment. The lime nitrogen-free zone was placed in the untreated zone. Both bags without and with lime nitrogen were placed in the no-application plot. Four bags per treatment were collected before snow cover (late December) and another four bags per treatment were collected before spring tillage (mid-April). The collected rice straw in the bag was wiped clean of attached mud, and dried at 80 °C for 48 h. After measuring the dry matter weight, the rice straw was ground, and the nitrogen and carbon concentrations were measured using an N/C analyzer (NC-22F, Sumika Chemical Analysis Service, Osaka, Japan), and the decomposition rate were calculated.

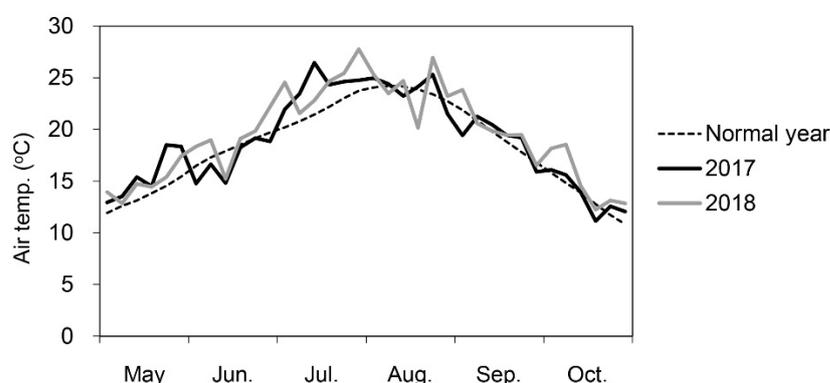
Soil temperature at 5 cm depth were measured at 1 h intervals using a data logger with a thermistor thermometer (Ondotori, TR-71U, T&D Corporation). The measurements were carried out in four replicates for autumn plowing and spring plowing plots, respectively.

### 2.1.3. Outline of Rice Cultivation

An outline of the paddy rice cultivation is shown in Table 3. In this process, 5 g m<sup>-2</sup> each of N, P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O was applied in mid-April using a chemical fertilizer (N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O: 13%-13%-13%) as a basal fertilizer, and the entire field was plowed (10 cm); rice straw remaining on the soil surface in the spring plowing plot was also plowed into the soil. In 2018, field management and rice transplanting were conducted about one week to ten days earlier than in 2017. In 2018, the cultivation was brought forward to secure the ripening period. Top-dressing fertilizer was applied as needed. Only in 2017 was mid-season drainage conducted. The final drainage was at the end of July, and harvesting was conducted in mid-October.

### 2.1.4. Climate

Meteorological data for temperature and precipitation were taken from the AMeDAS data of Ogata, Akita Prefecture, which is located in the studied center. The seasonal changes in the mean air temperature during the rice growing season in 2017 and 2018 are shown in Figure 1. The mean air temperatures in 2018 were higher in early June and during July compared to 2017.



**Figure 1.** Seasonal changes in air temperature during the rice growing season (May to October). The normal year is the average of the values for the past 30 years (1981–2010). The average values of every five days are shown.

### 2.1.5. GHG Fluxes

CH<sub>4</sub> and N<sub>2</sub>O fluxes during the rice growing season were measured per week by the closed chamber method [19–23]. Measurements were made in triplicate for each treatment with one point per plot. After rice transplanting, boardwalks were placed in the field to avoid any disturbances during flux measurements. A transparent acrylic chamber (30 × 60 × 50 cm [19]) was used for measurements. During the flux measurements, four rice plants were included inside the chamber. After late July, when the height of rice plants was over 50 cm, the chambers were stacked in two layers (1 m high). The chamber was covered with a lid and the initial collection time was set to 0 min. After 10 and 20 min, 20 mL of the gas sample from the chamber was collected in a vacuum vial (10 mL) with a butyl rubber septum. Simultaneously with the measurement, the soil temperature (5 cm depth) and the air temperature inside the chamber were measured using a thermometer. A stainless-steel cylindrical chamber (18.5–21.0 cm in diameter and 25 cm in height, [24,25]) was used for flux measurements after rice harvest.

The CH<sub>4</sub> and N<sub>2</sub>O concentrations were determined using a gas chromatograph (GC-14B, Shimadzu, Kyoto, Japan) equipped with a flame ionization detector (FID) and an electron capture detector (ECD), respectively (details for the analysis were provided in [21]). The GHG fluxes were calculated using a linear regression of the temporal changes in the gas concentrations inside the chamber. Cumulative GHG emissions during the measurement period were calculated by integrating the daily flux by linear interpolation.

The soil redox potential (Eh) and ferrous iron (Fe<sup>2+</sup>) content were also measured as environmental factors affecting GHG fluxes. Eh measurements were conducted simultaneously with each GHG flux measurement during the growing season. Two platinum electrodes were placed at a depth of 5 cm in each plot, and measurements were made using an Eh meter (PRN-41, Fujiwara Scientific Company Co., Ltd., Tokyo, Japan). The Fe<sup>2+</sup> content of the surface soil (0–10 cm) was measured by the acetate buffer extraction method. A total of five measurements were made from before flooding (late April) to before the final drainage (late July).

### 2.1.6. Growth and Yield of Rice

The number of tillers was measured seven to eight times periodically during the rice growing season. The number of tillers after the full heading stage (late August) corresponded to the number of panicles. The survey was conducted on 10 consecutive rice plants per plot. Yield and yield components were investigated in mid-October. In each plot, 48 rice hills were harvested and dried for yield measurement. After air-drying, threshing, and wind selection, the unhulled rice was hulled and sieved (1.9 mm mesh). The weight of the hulled rice (i.e., brown rice yield) was expressed as 15% moisture content. A portion of the brown rice was also used to determine the 1000-kernel weight. The number of panicles was taken from the growth survey described above. Two plants with an average number of panicles were selected from each plot and measured for the number of spikelets per panicle and the rate of filled spikelets (ripening rate).

## 2.2. Incubation Experiment for Rice Straw Decomposition

To elucidate the effect of different soil pH on the promotion of rice straw decomposition by lime nitrogen addition, an incubation experiment was conducted following the method of Nakajima et al. (2016) [26].

The soil collected from the plowed layer of a paddy field with gray lowland soil in Akita Prefecture was air-dried and used for the experiment. Rice straw of a staple rice variety (Hitomebore) was dried at 80 °C and then ground. Lime nitrogen was used in powder form. Calcium carbonate was added to 50 g of air-dried soil C at a rate of 0 or 1000 mg 100 g<sup>-1</sup> dry soil. Distilled water was added to make 40% of water filled pore space (WFPS), and the soil was incubated aerobically at 30 °C for two weeks. The WFPS of incubated soil was calculated by assuming its bulk density and particle density as 1.00 and

2.65 Mg m<sup>-3</sup>, respectively. The soil pH measured after the incubation (preincubation) was 5.9 and 8.1 for 0 and 1000 mg 100 g<sup>-1</sup> dry soil addition, respectively.

Aerobic incubation tests were conducted with three replicates of each of the six treatments, which were a combination of two soil pH levels (5.9, 8.1) and three treatments of addition (no addition, rice straw, and rice straw + lime nitrogen). The soil after pre-cultivation (equivalent to 2.5 g of dry soil) was taken in a 34 mL pressure-resistant test tube. Then, 50 mg of rice straw and 1.65 mg of lime nitrogen were added, and water was added to make the WPFS 60%. After one, two, three, and four weeks, the gas in the headspace was collected with a syringe and analyzed for CO<sub>2</sub> concentration using a gas chromatograph (GC-8A, Shimadzu, Kyoto, Japan) equipped a thermal conductivity detector (TCD). After each measurement, the test tubes were opened and sealed again by replacing with pure air, and the incubation was continued. The decomposition rate of rice straw-derived carbon was calculated from the cumulative CO<sub>2</sub> emission.

### 2.3. Statistical Analysis

For all of the statistical analyses, Excel statistics 2012 for Windows (SSRI, Tokyo, Japan) was used. For the field experiment, a three-way ANOVA was used, with three factors: year, plowing time, and lime nitrogen application. For the incubation experiment, a *t*-test was used. In this study, differences with *p* < 0.10 were considered significant.

## 3. Results

### 3.1. Decomposition of Rice Straw

The carbon decomposition rate and C/N ratio of rice straw before spring plowing are shown in Table 4. The decomposition rates of carbon derived from rice straw in autumn plowing plots were significantly higher than that in spring plowing plots. The carbon decomposition rate was also significantly increased by the application of lime nitrogen. However, the carbon decomposition rates in the spring plowing plots were increased by lime nitrogen application in 2017, but decreased by lime nitrogen application in 2018. Comparing the values of 2017 and 2018, the carbon decomposition rate in 2017 was significantly higher than that in 2018 by 8 to 10 points.

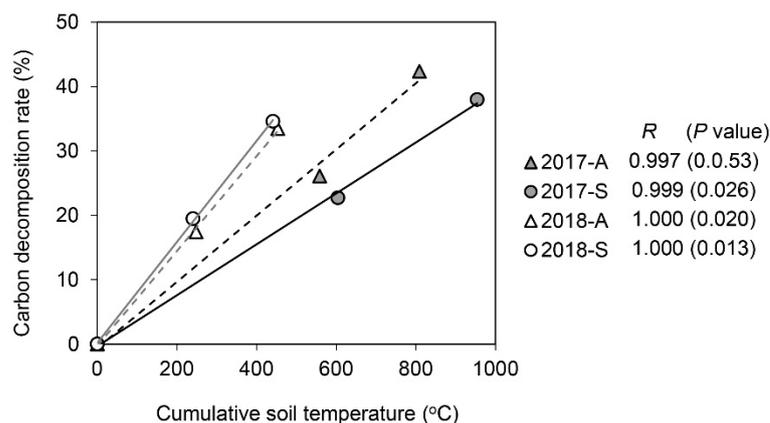
**Table 4.** Carbon decomposition rate and C/N ratio of rice straw (collected in early April before spring tillage).

Treatment	Carbon Decomposition Rate (%)		C/N Ratio	
	2017	2018	2017	2018
NA-S	38.0 ± 1.3	34.6 ± 2.2	68.5 ± 2.7	66.3 ± 2.2
LN-S	43.5 ± 1.2	31.5 ± 1.1	55.0 ± 2.9	73.9 ± 1.3
NA-A	42.4 ± 1.5	33.4 ± 1.5	54.6 ± 0.9	74.8 ± 2.5
LN-A	44.4 ± 0.5	36.7 ± 1.9	45.5 ± 1.7	68.8 ± 3.6
[Three-way ANOVA]				
Source	<i>p</i> value			
Year	**		**	
Incorporation	*		*	
LN addition	†		*	
Year × Incorporation	0.750		**	
Year × LN addition	†		**	
Incorporation × LN addition	0.503		0.276	
Year × Incorporation × LN addition	*		*	

Mean ± standard error. † *p* < 0.10, \* *p* < 0.05, \*\* *p* < 0.01. A, autumn; LN, lime nitrogen; NA, no application; S, spring.

The relationship between cumulative soil temperature and rice straw carbon decomposition rate during the fallow season is shown in Figure 2. The cumulative soil temperature in the experiment in 2017 was higher than that in 2018 by more than 300 °C before snow

cover and by 350–500 °C before spring plowing. This is mainly due to the difference in the start of the experiments in the previous year (2017: 12 October 2016 and 2018: 1 November 2017). There was a significant positive relationship between the cumulative soil temperature and rice straw decomposition rate; both the integrated soil temperature and rice straw decomposition rate were higher in 2017 than in 2018. However, the slope of the decomposition rate against the soil temperature in 2018 was higher than in 2017. In 2018, there was no difference in the carbon decomposition rate between the autumn and spring plowing plots, while in 2017, the carbon decomposition rate was higher in the autumn plowing plots than in the spring plowing plots.



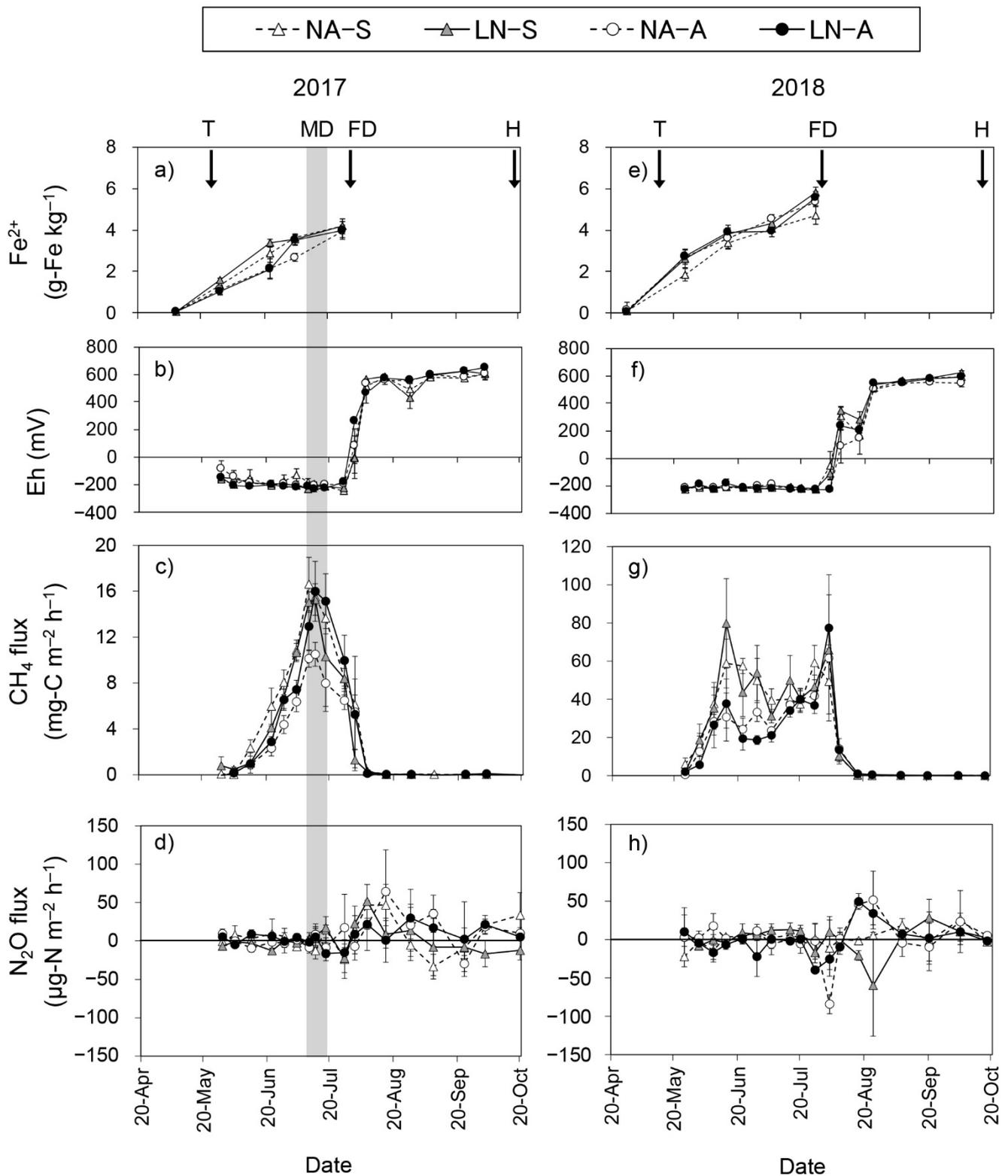
**Figure 2.** Relationship between the cumulative soil temperature and rice straw carbon decomposition rate (no lime nitrogen application plots) during the fallow season. A, autumn; S, spring.

### 3.2. $Fe^{2+}$ , Eh and GHG Fluxes

Seasonal changes in the soil ferrous iron content ( $Fe^{2+}$ ) in the plowed layer, soil redox potential (Eh) and  $CH_4$  and  $N_2O$  fluxes are shown in Figure 3. The  $Fe^{2+}$  content was higher in 2018 than in 2017 in both the autumn and spring plowing plots; it was lower in the autumn plots than in the spring plots in 2017, but there was no clear difference among the plots in 2018. The effect of lime nitrogen application on  $Fe^{2+}$  content was not significant. Eh in 2018 was slightly lower than in 2017 and was reduced below  $-200$  mV from the start of cultivation, with no difference between treatments. In both years, Eh increased from the time of final drainage and soil was in an oxidized state.

$CH_4$  fluxes peaked in July in 2017 and in June and August in 2018. In 2017, the maximum  $CH_4$  flux was about  $16 \text{ mg-C m}^{-2} \text{ h}^{-1}$ , and in 2018 it was about five times higher, at  $80 \text{ mg-C m}^{-2} \text{ h}^{-1}$ . In both years,  $CH_4$  fluxes decreased after the final drainage.  $N_2O$  fluxes remained around  $0 \text{ } \mu\text{g-N m}^{-2} \text{ h}^{-1}$  in all plots during the flooding period (from transplanting to final drainage). The  $N_2O$  fluxes were higher after the final drainage compared to the flooding period.

Cumulative  $CH_4$  and  $N_2O$  emissions are shown in Table 5.  $CH_4$  emissions in 2018 were significantly higher than in 2017, about six to seven times higher.  $CH_4$  emissions were significantly decreased by autumn plowing in both years. No decrease in  $CH_4$  emissions was observed with lime nitrogen application. Neither the timing of plowing nor the application of lime nitrogen had any effect on the  $N_2O$  emission. The  $CH_4$  emission accounted for the majority (95–100%) of the GWP. Therefore, there were differences in GWP between the years and the treatments similar to the trend in  $CH_4$ .



**Figure 3.** Seasonal changes in the soil's ferrous iron content ( $\text{Fe}^{2+}$ ) in the plowed layer (a,e), soil redox potential (Eh) at the 5 cm depth (b,f) and  $\text{CH}_4$  (c,g), and  $\text{N}_2\text{O}$  (d,h) fluxes in 2017 and 2018. Bars indicate standard errors. Positive flux values indicate emission to the atmosphere and negative values indicate uptake from the atmosphere. Only  $\text{CH}_4$  flux has a different y-axis range between 2017 and 2018. Mid-season drainage was carried out only in 2017. A, autumn; FD, final drainage; H, harvesting; LN, lime nitrogen; MD, mid-season drainage (gray area); NA, no application; S, spring; T, transplanting.

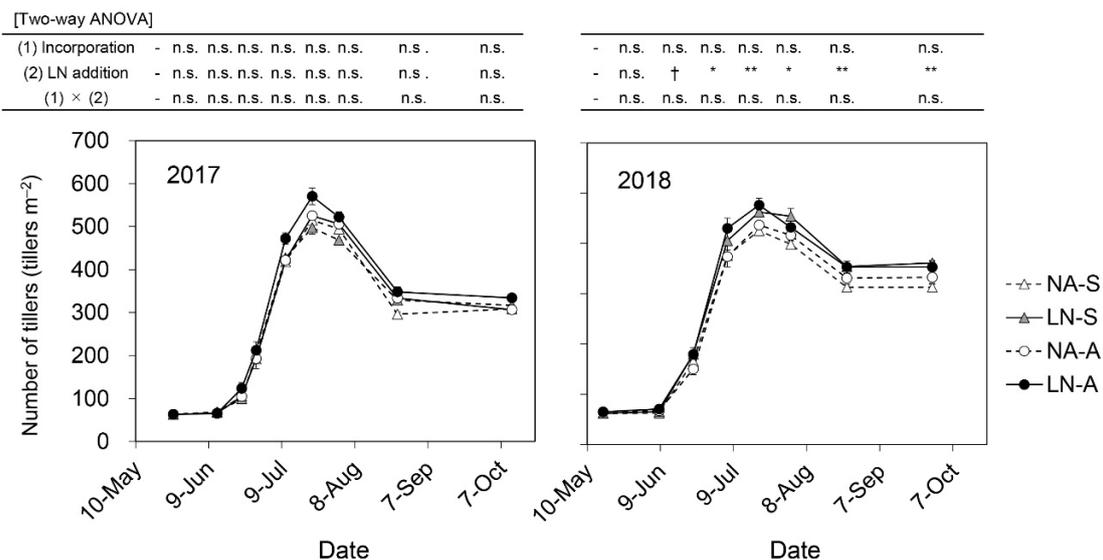
**Table 5.** Cumulative methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions for two years.

Treatment	CH <sub>4</sub> (g-C m <sup>-2</sup> )		N <sub>2</sub> O (mg-N m <sup>-2</sup> )		GWP (g-CO <sub>2</sub> eq m <sup>-2</sup> )	
	2017	2018	2017	2018	2017	2018
NA-S	12.3 ± 0.6	74.6 ± 10.8	22.1 ± 21.0	13.4 ± 11.7	568 ± 30	3390 ± 492
LN-S	10.3 ± 1.2	76.5 ± 12.7	1.3 ± 17.3	-0.2 ± 8.6	470 ± 49	3469 ± 577
NA-A	7.5 ± 0.9	58.9 ± 9.2	37.4 ± 39.4	17.2 ± 5.6	358 ± 36	2678 ± 419
LN-A	10.7 ± 2.1	56.2 ± 7.6	25.9 ± 30.5	4.7 ± 25.3	499 ± 108	2552 ± 334
[Three-way ANOVA]						
Source			<i>p</i> value			
Year	**		0.433		**	
Incorporation	†		0.459		†	
LN addition	0.982		0.376		0.995	
Year × Incorporation	0.146		0.633		0.142	
Year × LN addition	0.923		0.924		0.925	
Incorporation × LN addition	0.976		0.871		0.972	
Year × Incorporation × LN addition	0.644		0.898		0.641	

Mean ± standard error. Measurement period: 29 May–20 October (144 days) for 2017 and 25 May–18 October (146 days) for 2018, respectively. The GWP (global warming potential) was calculated by multiplying the CH<sub>4</sub> and N<sub>2</sub>O emissions by a coefficient (CO<sub>2</sub>:CH<sub>4</sub>:N<sub>2</sub>O = 1:34:298 [27]), converting them to CO<sub>2</sub>, and integrating them. † *p* < 0.10, \*\* *p* < 0.01. A, autumn; LN, lime nitrogen; NA, no application; S, spring.

### 3.3. Growth and Yield of Rice

The temporal changes in the number of tillers are shown in Figure 4. In both years, the number of tillers did not increase for about three weeks after transplanting. In 2017, the number of tillers increased significantly after late June, reaching a maximum of about 500–600 tillers m<sup>-2</sup>. Meanwhile, in 2018, although the maximum number of tillers was lower (400–500 tillers m<sup>-2</sup>), the final number of panicles was 10–60 panicles m<sup>-2</sup> higher than in 2017, and the rates of effective tillers (= panicle number / maximum tiller number × 100) were also higher (58–64% in 2017 and 74–78% in 2018). In 2017, the effects of plowing time and lime nitrogen application on the number of tillers were not observed, while in 2018, the number of tillers was significantly higher due to the application of lime nitrogen after late June.



**Figure 4.** Temporal changes in the number of tillers. The numbers of tillers after mid-August correspond to the numbers of panicles. Error bars indicate standard errors. † *p* < 0.10, \* *p* < 0.05, \*\* *p* < 0.01, n.s. *p* > 0.10. A, autumn; LN, lime nitrogen; NA, no application; S, spring.

The yield and yield components of rice are shown in Table 6. The number of panicles significantly increased with the application of lime nitrogen in both years. Application of lime nitrogen also significantly increased the 1000-kernel weight and brown rice yield, while the 1000-kernel weight and brown rice yield significantly increased with autumn plowing. In both years, the brown rice yield was the highest in the autumn plowing-lime nitrogen application plot (LN-A). The number of panicles, 1000-kernel weight and brown rice yield in 2018 were significantly higher than in 2017. However, the brown rice yield of all plots was below the target yield of 720 g m<sup>-2</sup> for Akita63 [18].

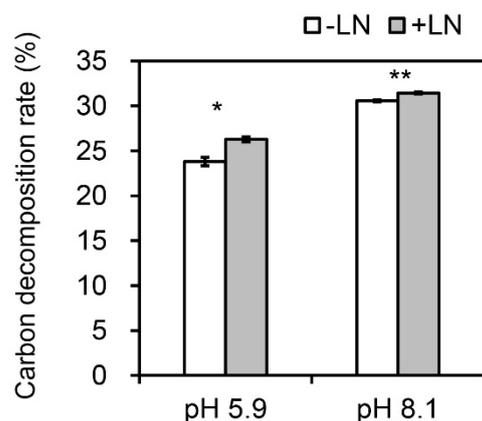
**Table 6.** Grain yield and yield component of rice for two years.

Year	Treatment	Number of Panicles (m <sup>-2</sup> )	Number of Spikelets per Panicle	Total Number of Spikelets (×10 <sup>3</sup> m <sup>-2</sup> )	Filled Spikelets (%)	1000-Kernel Weight <sup>a</sup> (g)	Grain Yield <sup>a</sup> (Brown Rice) (g m <sup>-2</sup> )
2017	NA-S	309	88.7	27.5	77.0	28.4	511
	LN-S	317	91.3	29.3	77.6	28.9	556
	NA-A	306	88.2	26.7	74.8	28.7	538
	LN-A	334	95.5	32.0	74.6	29.6	648
2018	NA-S	313	87.7	27.1	62.4	29.5	639
	LN-S	362	89.4	32.2	65.2	29.9	666
	NA-A	333	81.6	27.4	62.2	29.7	676
	LN-A	353	88.0	31.1	62.8	30.0	698
[Three-way ANOVA] Source				p value			
Year	*	0.102	0.541	**	**	**	
Incorporation	0.208	0.641	0.349	0.569	†	†	
LN addition	*	0.871	0.220	0.608	*	*	
Year × Incorporation	0.503	0.314	0.135	0.446	0.601	0.844	
Year × LN addition	0.149	0.900	0.566	*	0.811	0.137	
Incorporation × LN addition	0.792	0.319	0.923	0.441	0.983	0.523	
Year × Incorporation × LN addition	0.204	0.840	0.265	0.717	0.796	0.466	

<sup>a</sup> The moisture contents were adjusted to 15%. †  $p < 0.10$ , \*  $p < 0.05$ , \*\*  $p < 0.01$ . A, autumn; LN, lime nitrogen; NA, no application; S, spring.

### 3.4. Incubation Experiment for Rice Straw Decomposition

Time course of CO<sub>2</sub> production rate in the incubation experiment for rice straw decomposition is shown in Figure S3. Carbon dioxide production from rice straw decomposition was high during the first two weeks of incubation and then gradually decreased. Figure 5 shows the effect of different soil pH on the decomposition rate of rice straw. The carbon decomposition rate was higher in the treatment with higher pH. The application of lime nitrogen increased the carbon decomposition rate by 2.5 points in the pH 5.9 treatment, while the increase in the carbon decomposition rate was smaller, at 0.4 points, in the pH 8.1 treatment.



**Figure 5.** Effect of different soil pH on the enhancement effect of lime nitrogen (LN) on rice straw decomposition. Error bars indicate standard errors. \*  $p < 0.05$ , \*\*  $p < 0.01$  ( $t$ -test).

## 4. Discussion

### 4.1. Effects on Rice Straw Decomposition

In this study, the autumn plowing of rice straw increased the carbon decomposition rate (−1 to 5 points) before spring plowing, but the application of lime nitrogen did not enhance the decomposition of rice straw-derived carbon (Table 4). In this study, the carbon decomposition rate of rice straw was about 30–40% before spring plowing. The decomposition rate of rice straw during winter in northern Japan has been reported to be about 46% (Fukushima Prefecture, [5]), 30–35% (Yamagata Prefecture, [14]), and 37–50% (Hokkaido, [28]). The values in this study were also within this range.

Field experiments using cellulose, the substrate of methane, reported that the decomposition enhancement effect burial in soil was lower in the region with wet winter conditions than in the region with a dry winter [29]. This is explained by the fact that the difference in the decomposition rate of rice straw between surface placement and burial is small in wet fields where the ground surface does not dry out easily [30]. In the western part of the Tohoku region, where this study site is located, the climate during the winter is wet, so there may have been little difference in the moisture status of the rice straw placed on the soil surface in the spring plowing plots and the straw buried in the soil in the autumn plowing plots. Therefore, it is possible that the straw decomposition enhancement effect of the autumn plowing was low in this study.

In addition to lowering the C/N ratio of rice straw by supplying nitrogen, lime nitrogen is known to have the effect of promoting decomposition by raising the pH near the rice straw through the supply of alkaline content [31]. There have been many reports on the enhancement of rice straw decomposition by the addition of lime nitrogen with the autumn plowing of rice straw. The increase in straw decomposition rate (%) by lime nitrogen application has been reported to be 10 points (Fukushima Prefecture, [5]), approximately 5 points (Iwate Prefecture, [32]), and 4 points (Yamagata Prefecture, [33]). In these reports, the soil pH was mainly weakly acidic, ranging from 5.5 to 6.2, so the decomposition of rice straw may have been accelerated by the alkaline effect. On the other hand, the study site is located in the polder of Hachirogata Lake and the soil pH is high, at over 7.3, due to the presence of many shells in the soil (Table 1). In the incubation experiment, it was found that the carbon decomposition rate of rice straw increased with an increase in soil pH, and that the decomposition enhancement effect of lime nitrogen was low under high pH conditions (Figure 5). From the above, it is possible to conclude that the decomposition-promoting effect of the alkali effect was low and the decomposition-promoting effect of lime nitrogen application was not observed because the study site was a field with high soil pH. Similarly, Shiono et al. (2020) [34] found that increasing the pH of paddy soil from 5.5 to 7.0 accelerated the decomposition of incorporated rice straw during the fallow season in a field experiment. On the other hand, they also reported that while the increase in pH

accelerated the decomposition of rice straw during the fallow season, it also increased the CH<sub>4</sub> emission during the rice growing season in the following year due to the enhanced decomposition of organic matter during the flooded condition. The high soil pH in this study may also be a factor in the high CH<sub>4</sub> emission.

Between the years, the carbon decomposition rate of rice straw in the 2018 experiment was significantly lower than that in the 2017 experiment (Table 4). This could be attributed to the different timing of rice straw plowing due to the different varieties grown in the previous year. In the studied field, before the start of the 2017 experiment (2016), an early maturing variety Akitakomachi (the cumulative air temperature from flowering to maturity is 950–1050 °C, [18]) was grown and harvested in late September. Akita 63, which was grown the following year (2017), is a late-maturing variety (cumulative air temperature from flowering to maturity is 1200–1250 °C, [18]) and requires more time for ripening, and so its harvest time was October 19, which is one month later than that of Akitakomachi (Table 3). Therefore, the time of plowing was one month later in the 2018 experiment than in the 2017 experiment. Therefore, in the 2018 experiment, straw spraying and decomposition did not start in October, which is important for straw decomposition, due to high soil temperature, and decomposition did not proceed as much as in 2017 because the cumulative soil temperature was lower (Table 4, Figure 2). It was clear that the decomposition of rice straw was regulated by the cumulative soil temperature. However, the reason why the slope of the decomposition rate against the cumulative soil temperature differed from year to year (decomposition was more advanced in 2018) needs to be further investigated in the future.

#### 4.2. Effects on CH<sub>4</sub> and N<sub>2</sub>O Emissions

In 2018, CH<sub>4</sub> fluxes peaked in mid-June and early August (Figure 3). In particular, the peak in June was lower in the autumn plowing plots. It has been reported that 60% of the contributions to CH<sub>4</sub> emissions in the first half of paddy rice growth (around June) is due to applied organic matter, such as rice straw [35], and the June peak of CH<sub>4</sub> flux in this study and the difference among the plots in CH<sub>4</sub> flux can be attributed to rice straw.

According to previous reports, the CH<sub>4</sub> emissions from rice paddies in the following year are reduced by autumn plowing [5,33], and the enhancement of rice straw decomposition by autumn plowing is considered to be a factor. In this study, the decomposition rates of rice straw in the autumn plowing plots were significantly higher than those in the spring plowing plots, and the amounts of CH<sub>4</sub> emission were lower (Tables 4 and 5). However, in some individual cases, CH<sub>4</sub> emissions were reduced even though rice straw decomposition was not enhanced by autumn plowing (e.g., no lime nitrogen application plots in 2018).

This may be due to the stubble left in the field. In fields with poor drainage, stubble is often harvested at a height of 10–15 cm above the ground surface to prevent mud from entering the combine harvester during harvest. The organic matter supply by stubble in paddy fields was reported to be 93–150 g m<sup>-2</sup> [36]. In this study, the stubble was harvested at a higher position (about 15 cm) than usual (5–10 cm), and so the amount of organic matter remaining in the field as stubble was estimated to be 260 g m<sup>-2</sup> (Figure S4) and could be higher than previously reported and may have been an important substrate for CH<sub>4</sub> production in addition to rice straw applied to the field (750 g m<sup>-2</sup>). Naser et al. (2007) [37] reported that the amount of rice residue (straw + stubble) remaining in a paddy field until the next spring correlated with the amount of CH<sub>4</sub> emissions during the following rice cultivation. Stubble left in the field at harvest was plowed into the soil with rice straw in autumn only in the autumn plowing plots. On the other hand, stubbles in the spring plowing plots remained in the field in the same condition as at harvest without being integrated into the soil until plowing in the following spring. The decomposition of the stubble in the autumn plowing plots was more advanced than those in the spring plowing plots, resulting in less substrate for CH<sub>4</sub> production and possibly lower CH<sub>4</sub> emissions.

The peak of CH<sub>4</sub> emissions in August was observed immediately after the final drainage. This is thought to be due to the release of CH<sub>4</sub>, which was retained in the ground during waterlogging, as the water level fell [38].

Previous studies ([5,33]) reported that the application of lime nitrogen accelerated the decomposition of rice straw and decreased the amount of CH<sub>4</sub> emissions. However, in this study, the application of lime nitrogen did not suppress CH<sub>4</sub> emissions. As described in the previous section, the application of lime nitrogen did not promote the decomposition of rice straw, so the effect on CH<sub>4</sub> emissions was considered to be small.

CH<sub>4</sub> emissions in 2018 were significantly higher than in 2017. In the 2018 experiment, the carbon decomposition rate of rice straw was significantly lower than that of 2017, which may indicate that there was more substrate for CH<sub>4</sub> production. The air temperature during the rice growing season in 2018 remained higher than in 2017, which may have resulted in more active CH<sub>4</sub> production. During the 2018 experiment, rice was transplanted earlier than in the 2017 experiment, so flooding started earlier, and the increase in Fe<sup>2+</sup>, which indicates the progress of the soil reduction state, was faster (Figure 3). The combination of the above factors may have caused the inter-annual differences in CH<sub>4</sub> emissions.

Since many of these factors can be attributed to the cultivation of high-yielding varieties, the cultivation of high-yielding varieties is likely to increase CH<sub>4</sub> emissions compared to normal varieties. High-yielding varieties produce more rice straw left in the field after harvest than normal varieties. In general, high-yielding varieties tend to be late-maturing. The cultivation of late-maturing varieties results in a later harvest and a later time for straw plowing after cultivation in autumn. As a result, straw decomposition is likely to be inadequate, resulting in an increase in the substrate for CH<sub>4</sub> production in the following year. In addition, late-maturing, high yielding varieties require early transplanting to ensure the ripening period is sufficient, which leads to a longer flooding period in the field. This prolonged flooding results in a prolonged period of reduced soil conditions suitable for CH<sub>4</sub> production. Hence, further measures to reduce CH<sub>4</sub> emissions are considered necessary in the cultivation of high-yielding varieties.

Nitrous oxide was hardly emitted during the flooding period. The N<sub>2</sub>O emissions increased slightly after the final drainage. It is believed that the contribution of rice straw to the generation of N<sub>2</sub>O is negligible and is mainly due to the applied nitrogen material (e.g., [39]), but in this study, no increase in N<sub>2</sub>O emissions was observed due to the application of nitrogen material (lime nitrogen).

#### 4.3. Effects on Rice Growth

The number of panicles significantly increased with the application of lime nitrogen throughout the two years. The brown rice yield in the autumn plowing with lime nitrogen plot was the highest among the plots in both years. The application of lime nitrogen increased the amount of nitrogen remaining in the soil, which may have increased the number of panicles due to increased tillering.

It has been reported that about 45% of the nitrogen derived from lime nitrogen, which is incorporated with rice straw after harvest in autumn, remains in the soil before rice cultivation in the following spring [6]. This may have increased the amount of nitrogen available for rice plants, leading to an increase in the number of tillers. However, it has been reported that the amount of material-derived nitrogen absorbed by the plant is about 3–6% (0.2–0.3 g-N m<sup>-2</sup>) of the total uptake [6], so the increase in nitrogen uptake in this study site (1 g-N m<sup>-2</sup> at the panicle initiation stage and 0.2–0.6 g-N m<sup>-2</sup> at the maturity stage; data not shown) was not due to material-derived nitrogen uptake alone. It is also possible that the alkali effect of lime nitrogen application increased the mineralization of soil nitrogen, or that nitrogen absorbed by rice straw was mineralized. The factors behind the increase in thousand-grain weight and brown rice yield due to autumn plowing are not clear, and will require further study.

## 5. Conclusions

Autumn plowing promoted the decomposition of rice straw, but the application of lime nitrogen did not show a consistent trend. The soil pH was high in this study area, and the alkaline effect of lime nitrogen may not have been significant. As with straw decomposition, CH<sub>4</sub> emissions were suppressed by autumn plowing, and there was no effect of lime nitrogen application. It was also suggested that the straw decomposition period may be shorter and the CH<sub>4</sub> emissions may be higher in high-yielding cultivars that require a longer ripening period than normal cultivars. The effect of both treatments on N<sub>2</sub>O emission was not confirmed. Both the autumn plowing of rice straw and lime nitrogen application were effective in promoting rice growth and increasing yield.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/article/10.3390/agriculture11121298/s1>, Figure S1: Cutting and spreading rice straw. Figure S2: Autumn plowing (27 October 2017). Figure S3: Time course of CO<sub>2</sub> production rate in the incubation experiment for rice straw decomposition. LN, lime nitrogen. Figure S4: Dry matter weight of stubble at different harvest heights. Harvested at 30-Sep 2016. Cultivar: Akitakomachi.

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