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メタデータ	言語: eng 出版者: 公開日: 2021-01-04 キーワード (Ja): キーワード (En): 作成者: 秋山, 博子, 山本, 昭範, 内田, 義崇, 星野, 裕子, 多胡, 香奈子, 王, 勇, 早津, 雅仁 メールアドレス: 所属:
URL	https://repository.naro.go.jp/records/4992

Type of paper: Special issues

Title:

Effect of low C/N crop residue input on N_2O, NO, and CH_4 fluxes from Andosol and Fluvisol fields

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Abstract

Crop residues are produced from agriculture in large amounts globally. Crop residues are known to be a source of nitrous oxide (N_2O); however, contrasting results have been reported. Furthermore, the effect of crop residues on nitric oxide (NO) and methane (CH_4) fluxes has not been well studied. We investigated N_2O, NO, and CH_4 fluxes after low C/N crop residue (cabbages and potatoes) inputs to lysimeter fields for two years using with automated flux monitoring system. Lysimeters were filled with two contrasting soil types, Andosol (total C: 33.1 g kg^{-1}; clay: 18%) and Fluvisol (17.7 g kg^{-1}; 36%). Nitrogen application rates were 250 kg N ha^{-1} of synthetic fertilizer and 272 kg N ha^{-1} of cow manure compost for cabbage, and 120 kg N ha^{-1} of synthetic fertilizer and 136 kg N ha^{-1} of cow manure compost for potato, respectively. Large N_2O peaks were observed after crop residues were left on the surface of the soil for 1 to 2 weeks in summer, but not in winter. The annual N_2O emission factors (EFs) for cabbage residues were 3.02% and 5.37% for Andosol and Fluvisol, respectively. Those for potatoes were 7.51% and 5.10% for Andosol and Fluvisol, respectively. The EFs were much higher than the mean EFs of synthetic fertilizers from Japan's agricultural fields (0.62%). Moreover, the EFs were much higher than the Intergovernmental Panel on Climate Change (IPCC) default N_2O EFs for synthetic fertilizers and crop residues (1%). The annual NO EFs for potatoes were 1.35% and 2.44% for Andosol and Fluvisol, respectively, while no emission was observed after cabbage residue input. Crop residues did not affect CH_4 uptake by soil. Our results suggest that low C/N crop residue input to soils can create a hotspot of N_2O emission, when temperature and water conditions are not limiting factors for microbial activity.

Keywords: N fertilizer application, methane oxidation, greenhouse gas emissions, nitrous oxide, nitric oxide

1. Introduction

Nitrous oxide (N_2O) is a greenhouse gas and also contributes to the destruction of stratospheric ozone (O_3) (Ciais et al., 2013). Agriculture accounts for 59% of global anthropogenic N_2O emissions (Ciais et al., 2013). Nitric oxide (NO) is a precursor of tropospheric O_3, which is a greenhouse gas formed by photochemical reactions (Pilegaard 2013). NO is also a precursor of nitric acid (HNO_3), a major component of acid deposition (Pilegaard 2013). Agricultural soil is also a source of NO, accounting for 10% of anthropogenic emission (Ciais et al., 2013). Nitrification and bacterial denitrification are major production processes of N_2O and NO, and other microbial processes, such as fungal and nitrifier denitrification, also produce N_2O and NO in soils (Hayatsu et al., 2008). However, nitrification rather than denitrification is the most important process leading to NO emissions (Pilegaard 2013, Meditents et al. 2015). Soil type affect nitrification and denitrification thus production and consumption of N_2O and NO (Firestone and Davidson, 1989). On the contrary, aerobic soils act as sinks for methane (CH_4), a greenhouse gas, through CH_4 oxidation by microorganisms (Aronson and Helliker, 2010). The CH_4 oxidation by soil accounts for 4% of the global CH_4 sink (Ciais et al., 2013). Forest soil is known to have higher CH_4 oxidation rates than grassland or arable soil. Plowing and fertilizer application are the main factors leading to a lower CH_4 oxidation rate in arable soil (Hutsch, 2001). Soil type also affect CH_4 uptake by soil (Le Mer and Roger, 2001; Aronson and Helliker, 2010).

The amount of crop residues exceeds agricultural production (Smil, 1999) and is estimated to be approximately 4 billion metric tons per year globally (Lal, 2005). The input of these residues into agricultural soil is beneficial to soil carbon (C) sequestration and improves soil quality and crop yield (Liu et al., 2014). Crop residues also improve physical environment of the soil (Li et al., 2019). However, crop residues are also known as a source of N_2O in agricultural ecosystems, although this has been less studied than other N sources, such as synthetic fertilizers and manures. Crop residues can promote denitrification even at medium soil water-filled pore space (WFPS) values (Li et al. 2016). Li et al (2013) reported that crop residue input enhanced soil N_2O production at aerobic conditions regardless of their C/N ratios, while net N mineralization was dependent on residue C/N ratios. Large N_2O emissions sometimes occur after input of crop residues to soil. Toma and Hatano (2007) observed significant N_2O emissions just after the input of crop residues with a low C/N ratio (onion and soybean: C/N = 12 and 15) but not for residues with a high C/N ratio (rice straw and wheat straw: C/N = 62 and 110) or without crop residues. Crop residues accounted for 73% of cumulative N_2O emissions in a cabbage field (Koga et al., 2004; residue C/N =11.5) and 65% of cumulative N_2O emissions in a lettuce field (Baggs et al., 2000; residue C/N = 7.5).

According to a review by Novoa and Tiejeda (2006), the mean N_2O emission factor (EF) for all crop residues was 1%, although reported values of N_2O emission from crop residues varied largely. The Intergovernmental Panel on Climate Change (IPCC) default N_2O EF for crop residue is the same as that for synthetic and organic fertilizer application (1%; IPCC, 2019). A meta-analysis by Chen et al. (2013) suggested that the mean N_2O emissions from all crop residues were comparable to those of synthetic fertilizers, whereas N_2O emissions from vegetable crop residues were much higher than those of cereals and legumes. Shan and Yan (2013) reported that crop residues applied with synthetic fertilizers inhibited N_2O emissions by 11.7% compared with synthetic fertilizers alone; however, N_2O emissions were significantly enhanced by 42.1% when crop residues alone were applied. However, other studies have found that high C/N ratio resides can stimulate denitrification and enhance N_2O emissions when synthetic fertilizers are applied (Guardia et al. 2016, Sarkodie-Addo et al. 2003). Moreover, straw amendment in conjunction with nitrate-N can stimulate denitrification and increase soil N_2O emissions even though it may decrease the overall $N_2O/(N_2O + N_2)$ product ratio (Wu et al. 2018, Senbayram et al., 2018). In contrast to the effects on N_2O, the effects of crop residues on NO and CH_4 emissions have not been well studied.

Akiyama et al. (2006) reviewed N_2O emissions from Japanese agricultural fields and found that mean N_2O emission from poorly drained soils such as Fluvisols was much higher than that of well-drained soils such as Andosols. The aims of this study are to investigate the effect of the input of low C/N crop residues on direct N_2O, NO, and CH_4 fluxes from two contrasting soils, an Andosol and a Fluvisol, and to elucidate the importance of crop residues as N_2O and NO sources.

2. Materials and methods

2.1. Field experiment settings

The experiment was carried out in the lysimeter fields at the Institute for Agro-Environmental Sciences, Tsukuba, Ibaraki, Japan (36°01′ N, 140°07′ E). The annual mean air temperature was 13.8 °C and the total annual precipitation mean was 1282.9 mm (30 years mean, 1981–2010, by the Japan Meteorological Agency). Lysimeter beds (9 m^2 [3 × 3 m], 1.2 m deep) were filled with one of two soil types: an Andosol (a volcanic ash soil) or a Fluvisol (a gray lowland soil). The experimental design was a randomized block design with 2 soils × 2 residue treatments (with or without residue) × 3 replicates. The soil properties are shown in Table 1.

The field experiment was conducted for 2 years, from 1 January 2012 to 31 December 2013. Cabbages (*Brassica oleracea* L.) were cultivated in spring (12 April to 26 June) and autumn (13 September to 10 December) of 2012. Potatoes (*Solanum tuberosum* L.) were cultivated in the spring (26 March to 21 June) and autumn (27 August to 11 November) of 2013. Both crops were planted in four rows placed 60 cm apart in each lysimeter plot.

An equal amount of synthetic fertilizers and cow manure compost for all plots was applied at the time of transplanting of cabbage seedlings and when planting of potato tubers for each crop season in accordance with local recommendations. The synthetic fertilizers contained 8% nitrogen (NH_4-N), 8% phosphorus (P_2O_5), and 8% potassium (K_2O) (w/w). For cabbages, the application rates of fertilizers containing N, P_2O_5, and K_2O were 250 kg N ha^{-1}, 250 kg P_2O_5 ha^{-1}, and 250 kg K_2O ha^{-1}, respectively. The application rate of cow manure compost was 20,000 kg ha^{-1} (272 kg N ha^{-1}). For potatoes, the application rates of fertilizers containing N, P_2O_5, and K_2O were 120 kg N ha^{-1}, 200 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1}, respectively. The application rate of cow manure compost was 10,000 kg ha^{-1} (136 kg N ha^{-1}). The remaining P_2O_5 and K_2O were applied as calcium superphosphate and potassium chloride, respectively. Each fertilizer was incorporated into the soil (to a depth of 15 cm) using a walk-behind rotary tiller.

The treatments were with residues (WR) or without residues (NR) (three replicates each). For cabbage residues with the WR treatment, the outer leaves were left on the soil surface for about a week after the harvest of cabbage heads; these residues were then incorporated into the soil to about 10 cm depth using the walk-behind rotary tiller. For potato residues with the WR treatment, all potato leaves and stems were roughly cut by hand 2 weeks before harvesting (7 June and 31 October) to simulate machine cutting of potato stems using a haulm topper. The potato crop residue, which was left on the soil surface after haulm cutting, partly decomposed in 2 weeks and was then partially incorporated into soil by lifting the ridge soil and digging out potatoes during harvesting. Haulm cutting is becoming a common practice for large-scale potato cultivation in Japan, as well as in major potato production countries, because of pressure from customers to reduce the amount of pesticides used for crop production. For the NR treatment, all above-ground residues were removed from the plots. The roots were left in the field for both treatments.

2.2 Measurements of N_2O, NO, and CH_4 fluxes

N_2O, NO, and CH_4 fluxes were measured every 4 h (six times per day) with an automated flux monitoring system from 1 January 2012 to 31 December 2013 (Akiyama et al., 2000). Automated closed transparent polycarbonate chambers were placed at the center of each plot to include two rows of plants, each with a cross-sectional area of 8100 cm^2 (90 cm × 90 cm) and a height of 60 cm. For the N_2O and CH_4 flux measurement, the lid of each chamber was automatically closed for 30 min, and four air samples were taken every 8.5 min during the time the chamber was closed. For the NO flux measurement, four air samples were taken every 8.5 min for 3 min (5.5 min to 8.5 min) during the time the chamber was closed, and the mean concentration of last 1 min (7.5 min to 8.5 min) was used for the flux calculation. The gas sample was drawn to the analysis room through a 10-m-long Teflon tube and was immediately analyzed after sampling. The concentration of N_2O was determined with a gas chromatograph (GC) equipped with an electron capture detector (GC-14B; Shimadzu Corp., Kyoto, Japan). The concentration of CH_4 was determined using a GC equipped with a flame ionization detector (GC-14B; Shimadzu Corp.). The concentration of NO was determined using a chemiluminescence NOx analyzer (model 42c; Thermo Environmental Instruments, Inc., Franklin, MA, USA). Daily fluxes were estimated by averaging six flux data for the day for each plot. Cumulative emissions were estimated by integrating the daily flux over the measurement period. Crop residue induced EFs (%) were calculated as: ((N_2O-N or NO-N from WR) – (N_2O-N or NO-N from NR))/(N input from residue) * 100.

2.3 Measurements and analysis of environmental factors

The volumetric water content was measured two times a day at depths of 5 and 10 cm by time-domain reflectometry moisture sensors (CS615; Campbell Scientific Instruments, Logan, UT, USA). For the Andosol, the soil moisture content was determined from a calibration curve for Andosols (Hatano et al., 1995). Rainfall data were obtained from the Weather Data Acquisition System of Institute for Agro-Environmental Sciences, National Agricultural Research Organization.

Soil mineral nitrogen (N) from depths of 0 to 5 cm was measured. For the analysis, 15-g samples of fresh soil were extracted with 100 mL of KCl solution (100 g KCl L^{-1}). The copper–cadmium reduction and a diazotization method were used to analyze NO_3^-, and the indophenol blue method was used to analyze NH_4^+, using a TRRACS continuous-flow analyzer (Bran + Luebbe, Norderstedt, Germany).

2.5 Statistical analysis

The significance of the differences in N_2O, NO, and CH_4 emissions was determined by two-way analysis of variance (ANOVA; 2 soil types × 2 treatments). The significance of difference in crop yield and residue was determined by t-test, and Levene’s test was used to assess the equality of variances. The Pearson correlation coefficient was used to identify significant associations between gas fluxes and environmental factors. All statistical analyses were performed using IBM SPSS version 24.0 (IBM Corp., Chicago, IL, USA).

3. Results and Discussions

3.1 Crop yield and amount of residue

No significant differences in the amount, N content, and C/N ratio of crop residues were observed between the two soil types (Table S1). The crop yield was generally not significantly different between soils, except that the crop yield in the Fluvisol was significantly higher than that in the Andosol for autumn cabbages in 2012. For spring and autumn cabbage heads, the C/N ratio of material grown in the Andosol was significantly higher than that grown in the Fluvisol. No significant difference was found in the C/N ratio for potato tubers. The C/N ratio of the cabbage and potato residues varied from 7.97 to 11.6; this is relatively low compared with cereal crop residues, where the C/N ratio commonly ranged from 50 to 150.

3.2 Soil mineral N

The soil NH_4^+-N content peaked just after fertilizer application, and then the NO_3^--N content peaked about 1 week after fertilizer application (Figs. 1 and 2, Tables S2 and S3). These changes of mineral N suggested that nitrification occurred after fertilizer application. The small increases of soil NO_3^--N content were observed with the WR treatment for the input of spring cabbage residues in the summer (Fig. 1a, 1c, 2a, 2c, Table S2, S3).

3.3 Direct N_2O emissions

The seasonal changes of environmental factors and gas fluxes are shown in Figs. 3, 4, 5, and 6. The N_2O fluxes increased after each fertilizer application (Figs. 4a, 4b, 6a, and 6b). The amounts and kinds of fertilizers were the same for both treatments and soil types, and the N_2O emissions after fertilizer application were not significantly different between the residue treatments within the same soil type (Tables S4 and S5), indicating that crop residues from previous crops did not affect N_2O emission. After the fertilizer application, the N_2O emission from the Andosol was significantly higher than that of the Fluvisol, except that no significant difference was observed for the autumn potato season in 2013 (Tables S4, S5).

In summer, high N_2O peaks were observed after the input of crop residues; especially high fluxes were observed after crop residues were left on the surface of soil for 1 to 2 weeks, and then the N_2O flux decreased after the incorporation of residues into soil (Figs. 4a, 4b, 6a, and 6b). Note that crop residues were incorporated into soil 1 to 2 weeks after the residue input in this study. If fresh residues were incorporated into soil, N_2O emission might be higher than that of residue left on soil surface (Muhammad et al. 2019). By contrast, crop residues did not increase the N_2O in winter. After the input of crop residues in summer, the N_2O emission of the Fluvisol (clay loam) was significantly higher than that of the Andosol (loam), in contrast to the pattern after fertilizer application. Nett et al. (2016) reported that soil texture affected N_2O emissions after crop residue input, i.e., N_2O emissions increased in the order; loamy sand < silt loam < sandy clay loam.

For spring crop seasons, the N_2O emissions after the input of residues were much higher than those after fertilizer application (Tables S4 and S5). However, for autumn crop seasons, the N_2O emissions after the input of residues were much lower than those after fertilizer application (Tables S4 and S5). High temperature was likely the reason for the high N_2O emission after the input of residues in summer (mean temperature during a month after the input of residues: 23.5 ºC for cabbages and 22.8 ºC for potatoes), whereas no N_2O increase was observed after the input of residues in winter (mean temperature during a month after input of residues: 3.7 ºC for cabbages and 10.4 ºC for potatoes) (Figs. 3a and 5a). Pearson's correlation analysis found a significant effect of temperature on N_2O emissions when the relationship between temperature and N_2O emission after input of crop residues in summer and winter was investigated (Table S8).

Nitrous oxide emission after the input of crop residues provided a substantial portion of the annual N_2O emission—27% to 50% of the annual emissions with the WR treatment—whereas N_2O emission after fertilizer application provided 29% to 62% of the annual emissions with the WR treatment (Fig. 7 and Tables S4, S5). The annual N_2O EFs induced by the crop residues of cabbages were 3.02% and 5.37% for the Andosol and Fluvisol, respectively (Table S4). The annual N_2O EFs induced by the crop residues of potatoes were slightly higher than those of cabbage, that is, 7.51% and 5.10% for the Andosol and Fluvisol, respectively (Table S5), although the reason for this difference was not clear due to interannual variation of precipitation and temperature. The differences between EFs of potatoes and cabbages were not only due to the type of crop and management, and also the different climatic conditions in both years (the amount and distribution of rainfall, and temperatures). The annual N_2O EF induced by the crop residues in our study was much higher than the global mean of the N_2O EF induced by crop residues, which was 1% (range: 0.47%–2.90%; Novoa and Tejeda, 2006). Moreover, the EFs were much higher than the mean EFs resulting from synthetic fertilizer application in Japan's agricultural fields (0.62%; Akiyama et al., 2006). Vinther et al. (2004) reported high crop residue-induced N_2O EF of 1.5% and 14.1% for organic farming in a crop rotation field. In addition, field studies reported large N_2O emissions after the input of low C/N crop residues to soil (Baggs et al., 2000; Hou and Tsuruta, 2003; Koga et al., 2004; Toma and Hatano, 2007). Pugasgaard et al. (2017) reported that N_2O emissions were correlated with N input in residues from the previous main crop and catch crop, whereas no significant correlation between N_2O emissions and N input in fertilizer or manure. Meta-analysis studies also showed that low C/N crop residues significantly increased the N_2O emission, whereas high C/N crop residues did not increase the N_2O emission (Shan and Yan, 2013; Charles et al., 2017; Chen et al., 2013). Chen et al. (2013) reported that N_2O emission from residues decreased with the increase of C/N ratios; however, amendment with residues could not reduce soil N_2O emissions, even for C/N ratios above ~30, the threshold for net N immobilization. Another meta-analysis reported that N_2O emission increased with the decrease of C/N ratio and crop residues with a C/N ratio lower than 21 significantly increased N_2O emission (Charles et al., 2017). The C/N ratio of the cabbage and potato residues in our study was lower than 21, varying from 7.97 to 11.6.

Pearson's correlation coefficients between soil environmental factors and N_2O fluxes after the input of residues to the WR treatment in summer showed that N_2O fluxes positively correlated with WFPS for both years regardless of soil types (Tables S6 and S7), indicating that soil water content was an important controlling factor for N_2O emissions after residue input. By contrast, the effects of temperature on N_2O emissions were unclear, and the temperature range (17 ºC to 29 ºC) during the test period suggests that temperature would not be a limiting factor for microbial activity. However, temperature was an important factor affecting N_2O emission after the input of residues when the N_2O emissions during summer and winter were compared (Table S8). These results suggest that low C/N ratio crop residues can emit a large amount of N_2O when the temperature and moisture conditions are adequate for microbial activity. Although the increase of soil mineral N after the input of residues was relatively small, except for the increases of soil NO_3^--N contents after the input of cabbage residues in summer (Figs. 1 and 2, Tables S2 and S3), the crop residues could affect denitrification rates and stimulate N losses from residual N coming from previous fertilizer application (Li et al. 2016). Also, the degradation of the actual crop residues left on the soil surface could be the source of microbial N_2O production. Crop residues contain both C and N; especially crop residue with low C/N ratio such as vegetables will be rapidly decomposed by microbes and can provide a hotspot for denitrification and consequent N_2O emission. Hoshino et al. (in preparation) investigated denitrifying fungi from the same Andosol and Fluvisol fields in spring and autumn potato crops in 2013. They found that after haulm cutting in summer, the N_2O was produced mainly in decaying crop residues, rather than the soil, although fungi with high N_2O production activities were found in the crop residues and soil. They also found that fungal and bacterial denitrification contributed to N_2O production. In addition, Yamamoto et al. (2017) investigated N_2O isotopomers after fertilizer application and input of residues in the same Andosol field in the 2013 spring potato season and found that nitrification was the predominant process of N_2O production after fertilizer application, whereas bacterial and fungal denitrification were important N_2O production processes after the input of crop residues. Li et al. (2016) reported the predominance of denitrification after crop residues addition. Our results suggested that crop residues with a low C/N ratio can promote bacterial and fungal denitrification and produce a large amount of N_2O when temperature and moisture condition are adequate for microbial activity, particularly in soils with high organic matter and clay content, in combination with the low soil pH, which promotes incomplete denitrification.

3.4. NO emissions

Similar to the effect on N_2O, the fertilizer application increased NO fluxes (Figs. 4c, 4d, 6c, and 6d). The amount and type of fertilizer application were the same among treatments, and the NO fluxes were generally not significantly different among the residue treatments (Tables S9 and S10). Regarding the effect of soil type, after fertilizer application, the NO emissions from the Andosol were significantly higher than those from the Fluvisol, except that no difference was observed for spring potatoes in 2013. The NO emissions from the Andosol were also higher than those of the Fluvisol in our previous report (Akiyama et al. 2015).

The input of potato residues increased the NO fluxes in the summer of 2013, but NO fluxes did not increase after the input of cabbage residues in the summer of 2012 (Figs. 4c, 4d, 6c, and 6d, Tables S9 and S10), although the reason for the difference was unclear. Crop residues did not increase the NO fluxes in winter, probably due to low temperature, similar to the emission results for N_2O. A meta-analysis by Liu et al. (2017) reported that soil NO emissions were significantly decreased by crop residue incorporation (−9%), although only 9 data was available for the analysis.

On an annual basis, the NO emissions were mostly generated by fertilizer application, rather than by crop residues (Fig. 7). NO emissions after fertilizer application provided 18% to 84% of the annual emission with the WR treatment, and the proportion was higher than for N_2O emissions. By contrast, the NO emissions after the input of crop residues provided 1.5% to 31% of the annual emission with the WR treatment, and the proportion was lower than that for N_2O emissions (27% to 50%). The annual NO EFs induced by the crop residues of cabbage was 0% for both soil types (Table S9), whereas for potatoes, the NO EFs were 1.35% and 2.44% for the Andosol and Fluvisol, respectively (Table S10). The NO EFs induced by crop residues for the spring crop season (0% to 4.70%) were much lower than the N_2O EFs induced by crop residues (3.96% to 14.6%). However, the difference was unclear for the autumn crop season due to the low emission of both gases (Tables S4, S5, S9, and S10). In contrast to N_2O EFs, NO EFs induced by crop residues were rarely reported. Liu et al. (2011) reported a NO EF induced by crop residues of wheat straw of 0.42%, which was lower than the N_2O EF of 2.32% induced by crop residues. The predominance of denitrification after crop residues input (Li et al. 2016, Yamamoto et al. 2016) would be the reason for the high N_2O emissions and the low NO emissions, which is mainly produced by nitrification (Pilegaard 2013, Meditents et al. 2015).

The Pearson's correlation coefficients between soil environmental factors and NO fluxes after the input of residues in the WR treatment in summer showed that the NO fluxes positively correlated with the WFPS (Tables S6 and S7), except that a negative correlation was found after the input of cabbage residues in the Andosol, whereas the NO flux was low (Tables S9). Our results suggest that the WFPS is an important controlling factor for NO emissions after the input of residues, similar to N_2O. In general, nitrification dominates at below 60% WFPS and denitrification dominates at above 60 % WFPS; thus, the ratio of NO:N_2O is often close to 1 at 60% WFPS (Pilegaard 2013). After crop residue input, WFPS varied from 33% to 55% for the Andosol and 40% to 62% for the Fluvisol, respectively (Figs 3 and 5), suggesting nitrification would be dominant in NR. However, in WR, crop residues could promote denitrification even at medium WFPS values (Li et al. 2016).

The correlations between temperature and NO fluxes were unclear (Tables S6 and S7), whereas the temperature range (17 ºC to 29 ºC) during the period would not be a limiting factor for a microbial activity. The correlation between the soil mineral N and NO fluxes were also unclear, whereas the soil mineral N did not increase after the input of residues except for small increases of soil NO_3^--N contents after the input of cabbage residues in spring (Figs. 1 and 2). When the relationship between temperature and NO emissions after the input of crop residues in summer and winter was investigated, Pearson's correlation analysis found a significant effect of temperature on NO emissions (Table S8).

Nett et al. (2015, 2016) reported ammonia (NH_3) emission factor for residue ranged from 0 to 1.6% after cauliflower residue input into fields with different soil types. Although NH_3 emission was not measured in this study, NH_3 emission might occurred after residue input.

3.5 CH_4 fluxes

Factors, such as soil type, aeration, and N availability, affect CH_4 uptake by soil (Le Mer and Roger, 2001; Aronson and Helliker, 2010). CH_4 uptake by the Andosol was significantly higher than the uptake by the Fluvisol ($P < 0.001$; Figs. 4e, 4f, 6e, and 6f, Tables S11 and S12), similar to the results of our previous studies (Akiyama et al. 2014, 2015). The annual CH_4 uptake by the Andosol (−2.56 to −4.59 kg CH_4 ha^{-1} year^{-1}) was one order of magnitude higher than the annual CH_4 uptake by the Fluvisol (−0.42 to −0.53 kg CH_4 ha^{-1} year^{-1}, Tables S11 and S12). Morishita et al. (2007) reported that the mean CH_4 uptake by the Andosol (−8.3 kg CH_4 ha^{-1} $year^{-1}$) was significantly higher than that by other soils (−1.75 kg CH_4 ha^{-1} $year^{-1}$) for forests in Japan. Our results were consistent with their results, although the values for agricultural soil were much lower than those for forest soils. Lower bulk density and higher porosity of Andosols would be the reason of high CH_4 uptake by Andosols (Morishita et al. 2007). Previous studies also reported that the CH_4 uptake by agricultural fields is lower than that taken up by forest soils (Smith et al., 2000; Le Mer and Roger, 2001; Suwanwaree and Robertson, 2005). Dutaur and Verchot (2007) summarized the reported values of CH_4 uptake by cultivated land (range: 0 to −4.23 kg CH_4 ha^{-1} $year^{-1}$, mean: −1.60 kg CH_4 ha^{-1} $year^{-1}$) and found that the uptake by the Andosol was higher than the reported range, whereas the uptake by the Fluvisol was in the lowest range.

Daily CH_4 flux values after fertilizer application were lower than those at other periods (Table S14). Nitrogen fertilizer application generally reduces CH_4 uptake by soil because ammonium blocks the methanotrophic enzyme system, resulting in an inhibition of CH_4 oxidation (Hutsch, 2001; Liu and Greaver, 2009). Pearson’s correlation coefficients between soil environmental factors and CH_4 fluxes showed no clear effect of WFPS and temperature on CH_4 fluxes during this period (data not shown).

According to a review by Hutsch (2001), crop residues affect CH_4 oxidation differently depending on their C/N ratio; that is, crop residues with a high C/N ratio, such as wheat straw, stimulate N immobilization with no effect on CH_4 oxidation, whereas crop residues with a low C/N ratio, such as sugar beet or potato leaves, enhance the N mineralization with a strong inhibition of the CH_4 oxidation because ammonium inhibits the methanotrophic enzyme system. However, residues of crops with a low C/N ratio, such as cabbages (C/N = 10 to 11) and potatoes (C/N = 8 to 12), did not affect the CH_4 uptake by soil in this study (Figs. 4e, 4f, 6e, and 6f, Tables S11 and S12). Jacinthe and Lal (2003), Sanz-Cobena et al. (2014), and Guardia et al. (2016) also reported that cover crop residues with low C/N and high C/N ratios did not affect the CH_4 uptake. By contrast, sugarcane residue (C/N = 51) increased the CH_4 uptake by 40% compared with the amount taken up by bare soil (Vasconcelos et al., 2018).

4. Conclusions

We investigated the effect of low C/N crop residues on N_2O, NO, and CH_4 fluxes in fields with two contrasting soil types, Andosol and Fluvisol. High N_2O peaks were found when crop residues were left on the surface of the soil in summer but not in winter. Annual N_2O EFs induced by crop residues of cabbages were 3.02% and 5.37% for the Andosol and Fluvisol, respectively, and those for potatoes were 7.51% and 5.10% for the Andosol and Fluvisol, respectively. Annual NO EFs induced by crop residues of potatoes were 1.35% and 2.44% for the Andosol and Fluvisol, respectively, and the effect of cabbage residues on NO emissions was unclear. Crop residues did not affect CH_4 uptake by soil. Our results suggest that crop residues with a low C/N ratio, such as vegetables, can promote bacterial and fungal denitrification and consequently result in high N_2O emission, when temperature and water content are appropriate for microbial activity. The input of crop residues into agricultural soil is beneficial to soil C sequestration and improves soil quality and crop yield (Liu et al., 2014), thus further research is needed to mitigate N_2O emissions from low C/N crop residue application such as application methods (e.g., mulching vs incorporation).

5. Acknowledgments

This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI 26292184 and 18H02318.

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Figure legends

Fig. 1

Seasonal changes in 2012 of (a) soil NO_3^--N content in the Andosol, (b) soil NH_4^+-N content in the Andosol, (c) soil NO_3^--N content in the Fluvisol, and (d) soil NH_4^+-N content in the Fluvisol. Error bars represent the standard deviation of replicate plots (n = 3). The vertical arrows indicate the times of fertilizer application (F), input of residues after haulm cutting (R), and incorporation of residues (I).

Fig. 2

Seasonal changes in 2013 of (a) soil NO_3^--N content in the Andosol, (b) soil NH_4^+-N content in the Andosol, (c) soil NO_3^--N content in the Fluvisol, and (d) soil NH_4^+-N content in the Fluvisol in 2012. Error bars represent the standard deviation of replicate plots (n = 3). The vertical arrows indicate the times of fertilizer application (F), harvest (H), and incorporation of residues (I).

Fig. 3

Seasonal changes of cabbage fields in 2012 in terms of (a) air temperature (daily mean), (b) daily precipitation (bars) and water-filled pore space (WFPS) (line).

Fig. 4

Seasonal changes of cabbage fields in 2012 in terms of (a) N_2O fluxes from the Andosol, (b) N_2O fluxes from the Fluvisol, (c) NO fluxes from the Andosol, (d) NO fluxes from the Fluvisol, (e) CH_4 fluxes by the Andosol, and (f) CH_4 fluxes by the Fluvisol. The vertical arrows indicate the times of fertilizer application (F), harvest of cabbage heads (H), and incorporation of residues (I).

Fig. 5

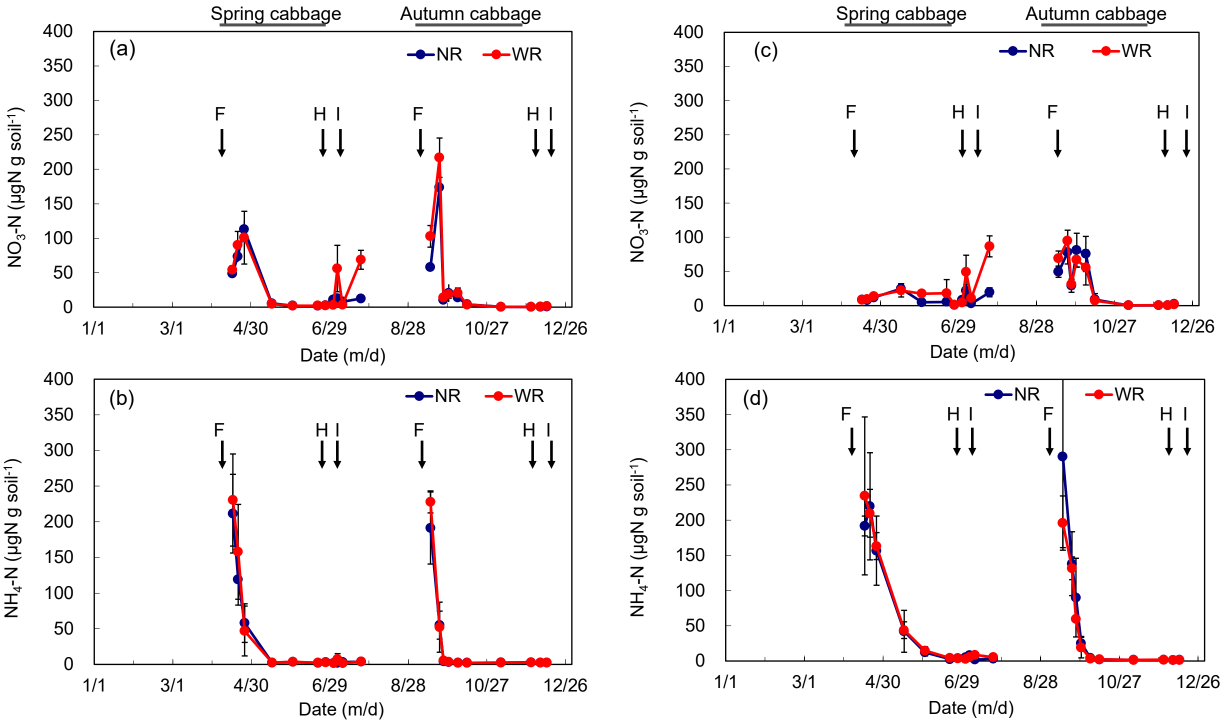
Seasonal changes of potato fields in 2013 in terms of (a) air temperature (daily mean), (b) daily precipitation (bars) and water-filled pore space (WFPS) (line).

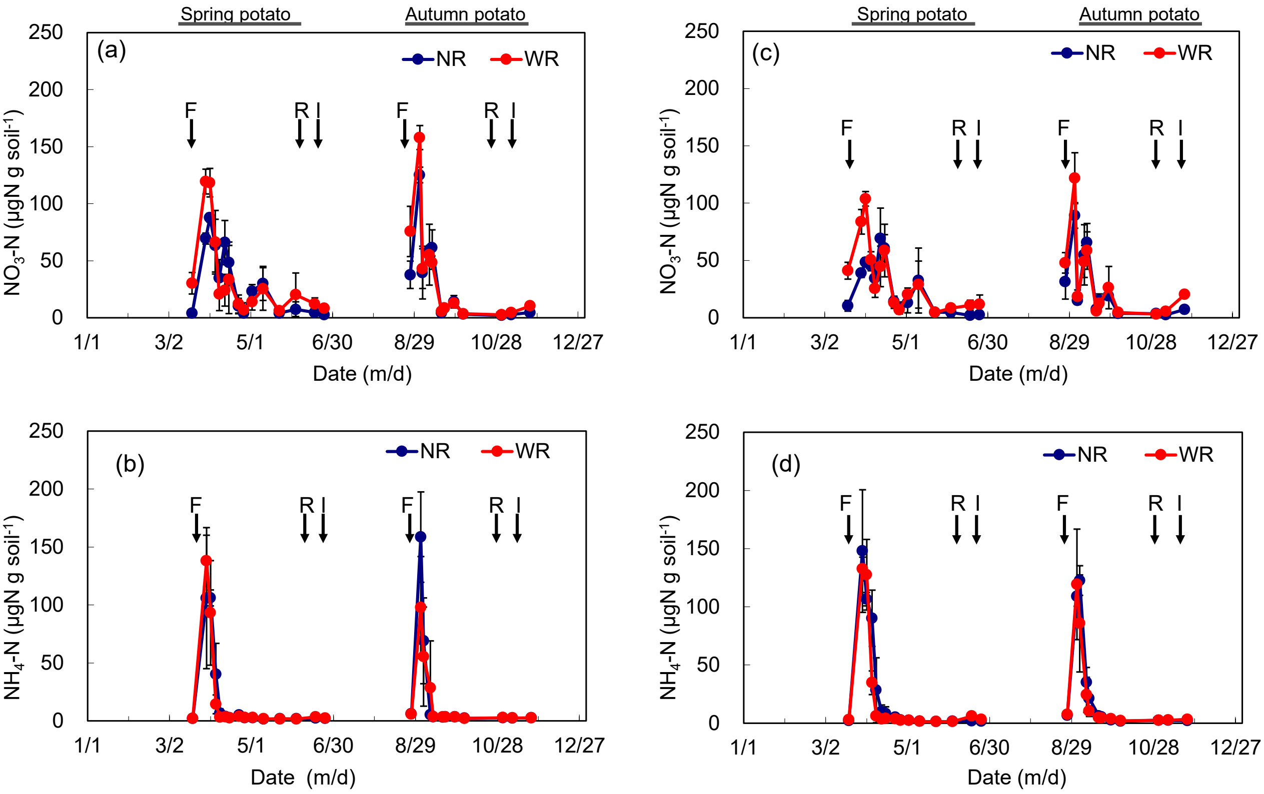
Fig. 6

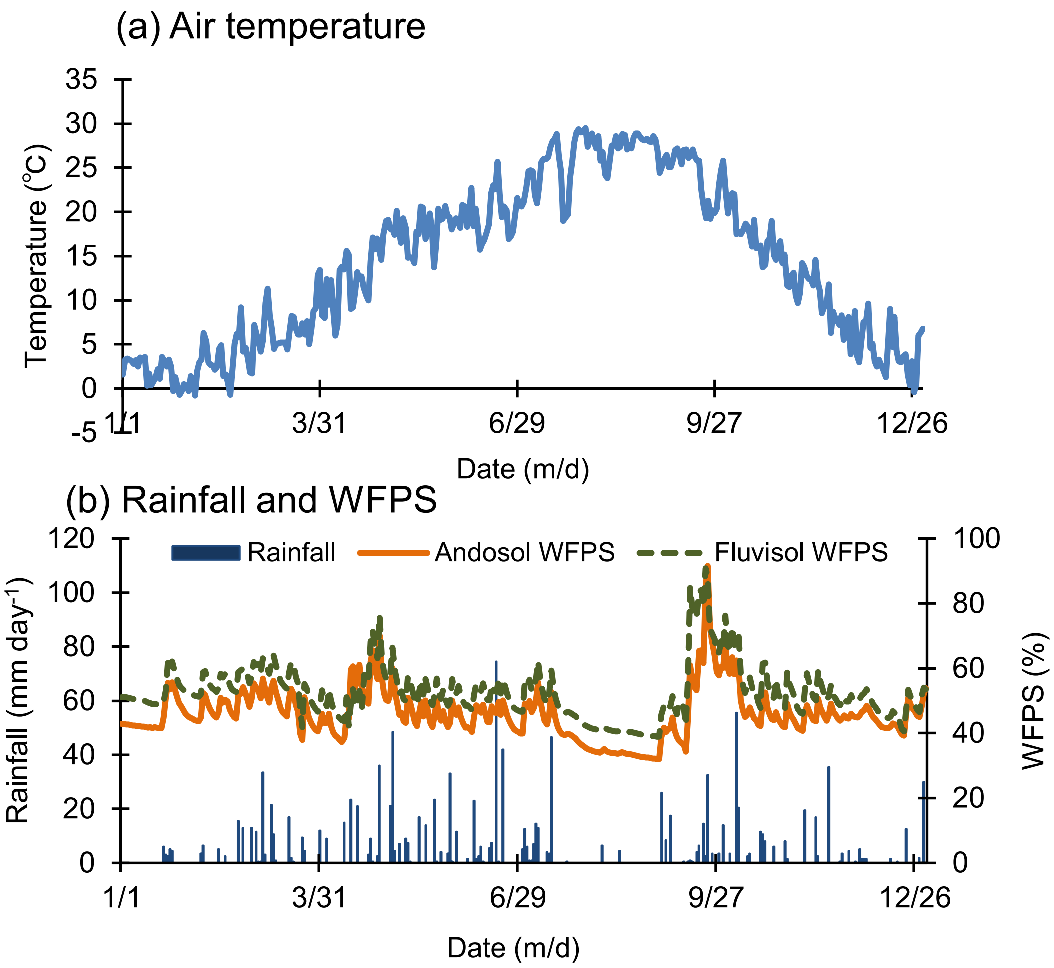
Seasonal changes of potato fields in 2013 in terms of (a) N_2O fluxes from the Andosol, (b) N_2O fluxes from the Fluvisol, (c) NO fluxes from the Andosol, (d) NO fluxes from the Fluvisol, (e) CH_4 fluxes by the Andosol, and (f) CH_4 fluxes by the Fluvisol. The vertical arrows indicate the times of fertilizer application (F), input of residues after haulm cutting (R), and incorporation of residues (I).

Fig. 7

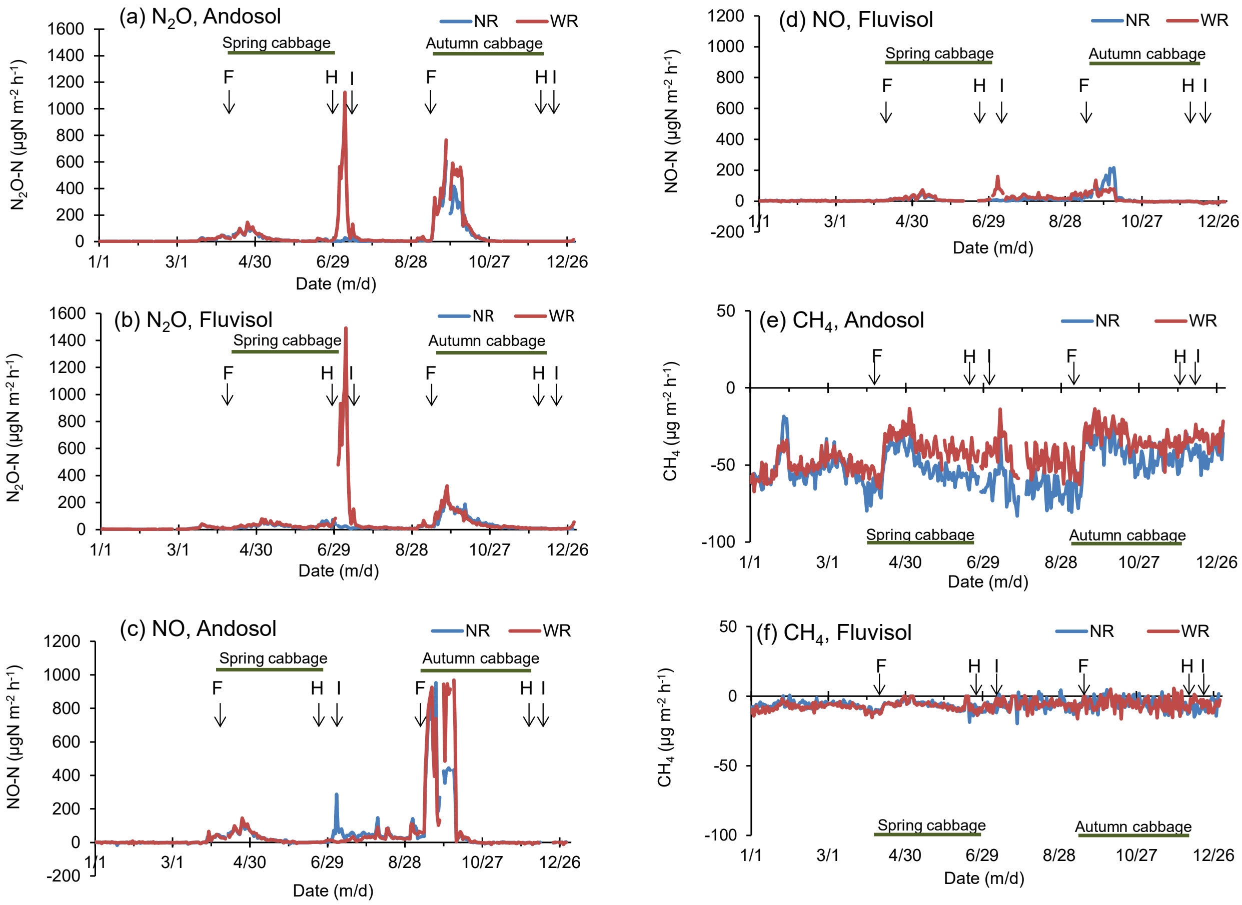
(a) Annual N_2O emissions from the Andosol and the Fluvisol in 2012, (b) annual N_2O emission from the Andosol and the Fluvisol in 2013, (c) annual NO emission from the Andosol and the Fluvisol in 2012, and (d) annual NO emission from the Andosol and the Fluvisol in 2013. Annual emissions were divided into three periods, namely, 30 days after fertilizer application ("after fertilizer"), 30 days after input of residues ("after residue") (note that the residues were applied only for the WR treatment, and no residue was applied for the NR treatment during the same period), and "other period." Error bars represent the standard deviation of replicate plots ($n = 3$). For statistical analysis, log-transformed data were tested with two-way ANOVA. Significance is indicated by *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$; ns, not significant.


Spring cabbage
Autumn cabbage
(a)
(b)
(c)
(d)
NR
WR
F
H
I
NO_3-N (μgN g soil^{-1})
NH_4-N (μgN g soil^{-1})
Date (m/d)
1/1
3/1
4/30
6/29
8/28
10/27
12/26
0
50
100
150
200
250
300
350
400

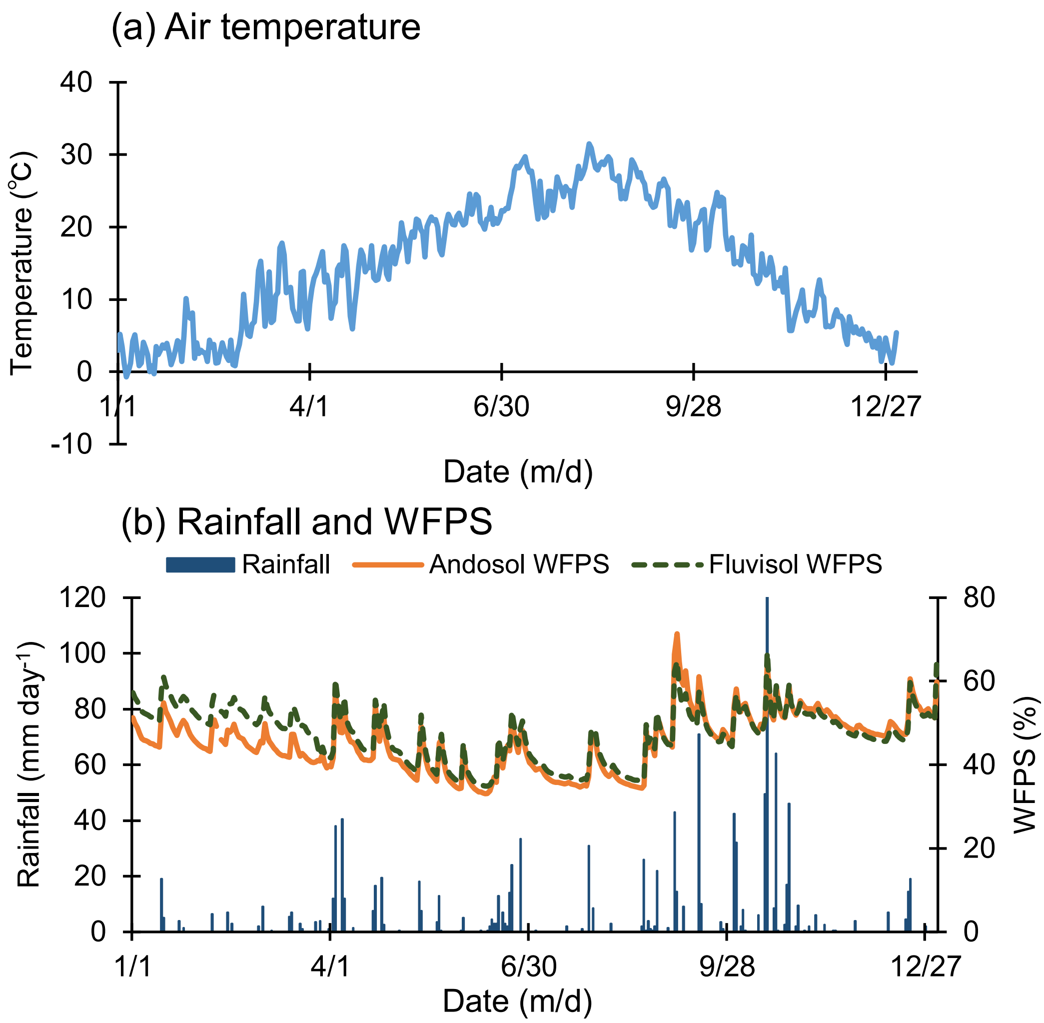

Spring potato
Autumn potato
(a)
(b)
(c)
(d)
NR
WR
F
R
I
NO3-N (µgN g soil-1)
NH4-N (µgN g soil-1)
Date (m/d)
1/1
3/2
5/1
6/30
8/29
10/28
12/27
0
50
100
150
200
250

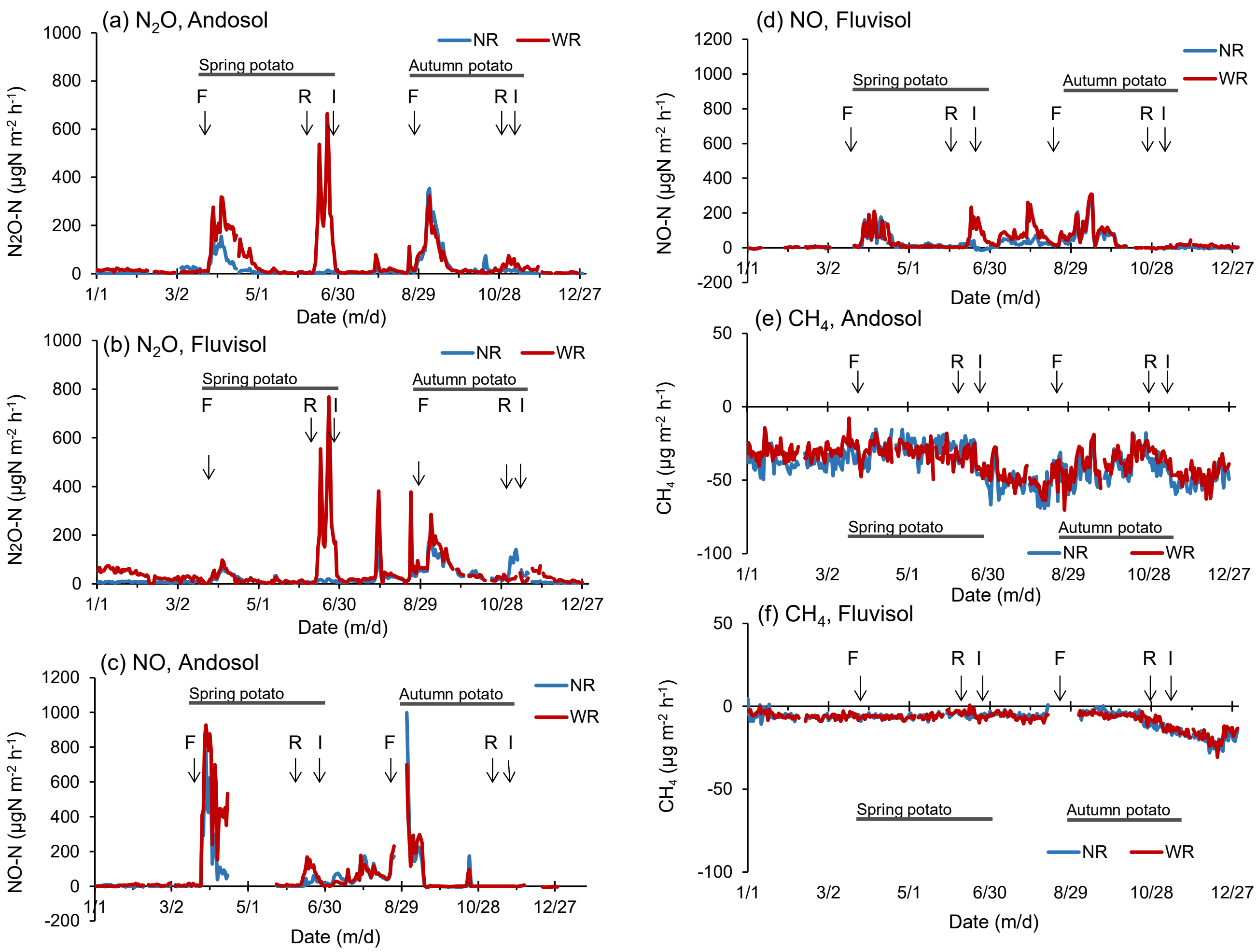


(a) Air temperature
Temperature (°C)
35
30
25
20
15
10
5
0
-5
1/1
3/31
6/29
9/27
12/26
Date (m/d)
(b) Rainfall and WFPS
Rainfall
Andosol WFPS
Fluvisol WFPS
Rainfall (mm day-1)
120
100
80
60
40
20
0
WFPS (%)
100
80
60
40
20
0
1/1
3/31
6/29
9/27
12/26
Date (m/d)



(a) N_2O, Andosol
(b) N_2O, Fluvisol
(c) NO, Andosol
(d) NO, Fluvisol
(e) CH_4, Andosol
(f) CH_4, Fluvisol
NR
WR
Spring cabbage
Autumn cabbage
F
H
I
N_2O-N (μgN m^{-2} h^{-1})
NO-N (μgN m^{-2} h^{-1})
CH_4 (μg m^{-2} h^{-1})
Date (m/d)
1/1
3/1
4/30
6/29
8/28
10/27
12/26


(a) Air temperature
Temperature (°C)
40
30
20
10
0
-10
1/1
4/1
6/30
9/28
12/27
Date (m/d)
(b) Rainfall and WFPS
Rainfall
Andosol WFPS
Fluvisol WFPS
Rainfall (mm day-1)
120
100
80
60
40
20
0
WFPS (%)
80
60
40
20
0
1/1
4/1
6/30
9/28
12/27
Date (m/d)


(a) N2O, Andosol
(b) N2O, Fluvisol
(c) NO, Andosol
(d) NO, Fluvisol
(e) CH4, Andosol
(f) CH4, Fluvisol
NR
WR
Spring potato
Autumn potato
F
R
I
N2O-N (μgN m-2 h-1)
NO-N (μgN m-2 h-1)
CH4 (μg m-2 h-1)
Date (m/d)
1/1
3/2
5/1
6/30
8/29
10/28
12/27

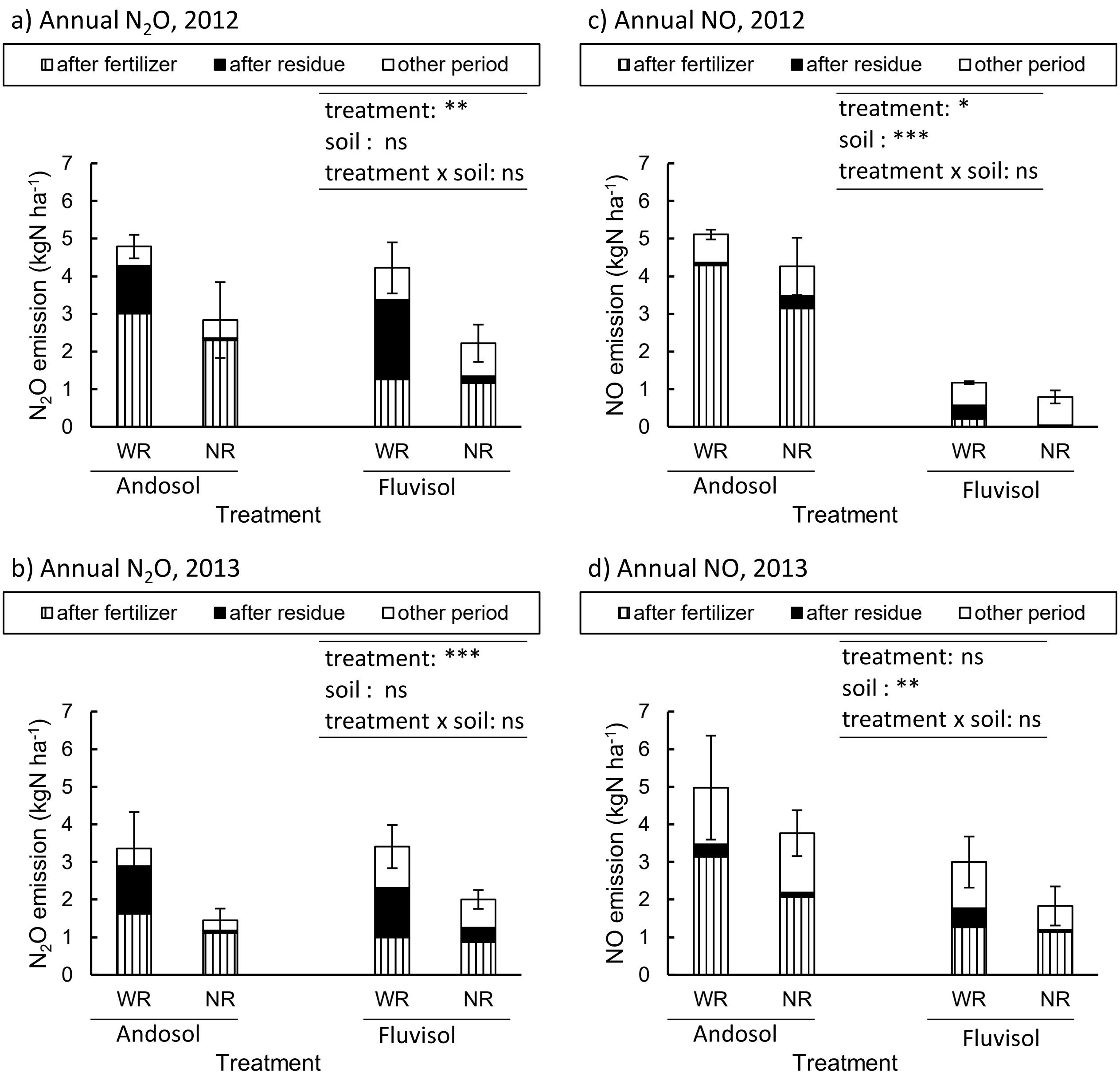

a) Annual N2O, 2012
after fertilizer
after residue
other period
treatment: **
soil : ns
treatment x soil: ns
N2O emission (kgN ha-1)
0
1
2
3
4
5
6
7
WR
NR
WR
NR
Andosol
Fluvisol
Treatment
b) Annual N2O, 2013
after fertilizer
after residue
other period
treatment: ***
soil : ns
treatment x soil: ns
N2O emission (kgN ha-1)
WR
NR
WR
NR
Andosol
Fluvisol
Treatment
c) Annual NO, 2012
after fertilizer
after residue
other period
treatment: *
soil : ***
treatment x soil: ns
NO emission (kgN ha-1)
WR
NR
WR
NR
Andosol
Fluvisol
Treatment
d) Annual NO, 2013
after fertilizer
after residue
other period
treatment: ns
soil : **
treatment x soil: ns
NO emission (kgN ha-1)
WR
NR
WR
NR
Andosol
Fluvisol
Treatment

Table 1 Soil properties

	pH (H_2O)	CEC (cmol(+) kg^{-1})	AEC[#] (cmol(-) kg^{-1})	Total C (g kg^{-1})	Total N (g kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Texture	Dry bulk density (Mg m^{-3})	Hydraulic conductivity (m s^{-1})
Andosol	5.9	27.7	0.10	33.1	3.2	37	45	18	Loam	0.61	3.2×10^{-5}
Fluvisol	5.7	21.6	0.13	17.7	1.5	34	30	36	Clay loam	0.85	2.0×10^{-6}

AEC: anion exchange capacity.
CEC: cation exchange capacity.
AEC was measured by 0.002 M $BaCl_2$ equilibrium method (Analysis of Soil, Water, and Plant, 2001).

Supplemental materials

Title:

Effect of low C/N crop residue input on N_2O, NO and CH_4 fluxes from Andosol and Fluvisol fields

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Table S1. The amounts and CN ratios of crop residue and crop yield

Soil	Crop residue						Crop yield					
	amount (kg DW ha^{-1})		N (kg ha^{-1})		C:N ratio		amount (kg DW ha^{-1})		N (kg ha^{-1})		C:N ratio	
Spring Cabbage, 2012												
Andosol	3214±791	a	30.3±8.7	a	10.1±0.4	a	3732±910	a	49.5±11.5	a	11.0±0.44	a**
Fluvisol	2988±452	a	25.3±1.2	a	11.4±1.1	a	2885±492	a	42.6±6.0	a	8.98±0.96	b
Autumn Cabbage, 2012												
Andosol	693±14	a	9.81±1.85	a	11.3±1.0	a	850±139	a*	7.93±1.37	a*	14.7±0.6	a*
Fluvisol	912±120	a	10.5±1.0	a	11.0±0.5	a	1149±248	b	12.1±2.6	b	13.1±0.5	b
Spring Potato, 2013												
Andosol	743±139	a	7.08±1.17	a	11.6±0.3	a	3782±813	a	14.1±2.4	a	34.7±4.9	a
Fluvisol	817±93	a	8.00±1.42	a	11.2±1.0	a	3260±275	a	13.3±3.0	a	33.7±6.2	a
Autumn Potato, 2013												
Andosol	795±238	a	8.76±2.00	a	8.22±0.69	a	1236±289	a	7.24±1.49	a	23.1±1.1	a
Fluvisol	935±230	a	10.6±2.3	a	7.97±0.78	a	1633±424	a	12.6±9.9	a	24.5±1.8	a

Mean ± standard deviation of 6 replicates (residue treatments were not considered here because all agricultural practice including fertilizer application were the same for both NR (without residue) and WR (with residue).)

DW: dry weight

Different letter means significantly different by t-test. * $P < 0.05$, ** $P < 0.01$, ***

Table S2. Seasonal change of soil inorganic N in 2012

Date	Andosol				Fluvisol			
	NO_3^- (μgN g soil^{-1})		NH_4^+ (μgN g soil^{-1})		NO_3^- (μgN g soil^{-1})		NH_4^+ (μgN g soil^{-1})	
(m/d)	NR	WR	NR	WR	NR	WR	NR	WR
Spring cabbage								
4/16	48.6 ± 2.8	54.1 ± 6.0	211.4 ± 55.2	230.5 ± 64.6	8.7 ± 0.3	8.0 ± 0.4	191.8 ± 14.1	234.5 ± 112.2
4/20	73.5 ± 8.0	90.3 ± 19.6	119.2 ± 36.0	157.9 ± 66.5	7.9 ± 0.9	9.5 ± 2.1	219.7 ± 76.1	209.8 ± 33.9
4/25	112.8 ± 12.1	100.8 ± 38.3	57.9 ± 27.1	46.9 ± 35.0	11.8 ± 1.6	13.5 ± 2.3	156.7 ± 49.1	163.3 ± 19.2
5/16	5.3 ± 0.0	4.4 ± 1.1	2.5 ± 0.4	2.4 ± 0.9	24.6 ± 7.5	22.2 ± 9.6	42.2 ± 29.8	43.8 ± 11.9
6/1	2.2 ± 0.8	1.9 ± 0.5	3.4 ± 0.2	3.5 ± 0.2	4.8 ± 2.9	17.4 ± 3.1	12.3 ± 5.1	14.8 ± 5.5
6/20	1.8 ± 0.2	2.2 ± 0.7	2.1 ± 0.2	2.3 ± 0.2	5.3 ± 5.1	18.1 ± 20.0	2.7 ± 0.3	4.4 ± 3.2
6/26	2.6 ± 1.1	2.3 ± 0.6	3.1 ± 0.5	2.8 ± 0.1	1.0 ± 0.4	1.0 ± 0.2	3.9 ± 0.6	3.6 ± 0.6
7/2	10.8 ± 8.1	3.2 ± 0.7	2.0 ± 1.0	1.5 ± 0.2	8.2 ± 3.5	4.4 ± 3.6	5.0 ± 2.5	3.0 ± 0.6
7/5	12.7 ± 3.0	56.0 ± 33.7	1.9 ± 0.3	7.4 ± 7.8	21.8 ± 8.9	49.1 ± 24.6	8.1 ± 2.4	5.4 ± 2.2
7/9	8.0 ± 3.9	3.4 ± 0.4	3.3 ± 2.0	1.5 ± 0.5	3.1 ± 0.6	10.9 ± 2.2	2.1 ± 0.3	8.6 ± 3.6
7/23	12.3 ± 4.2	68.7 ± 13.7	3.7 ± 0.1	4.0 ± 1.1	19.5 ± 6.6	86.8 ± 15.4	3.4 ± 0.3	5.4 ± 0.9
Autumn cabbage								
9/14	57.8 ± 2.5	102.7 ± 15.7	191.3 ± 50.5	227.9 ± 15.4	49.5 ± 8.1	68.9 ± 11.0	290.5 ± 129.5	195.9 ± 38.5
9/21	173.8 ± 25.5	216.9 ± 28.6	55.1 ± 19.7	52.2 ± 35.1	77.9 ± 16.9	95.0 ± 15.4	138.3 ± 45.3	131.7 ± 16.1
9/24	10.3 ± 5.3	13.8 ± 4.8	4.1 ± 0.6	5.3 ± 2.2	29.3 ± 9.8	31.2 ± 6.8	90.0 ± 55.9	59.8 ± 4.7
9/28	20.4 ± 12.8	18.8 ± 5.9	3.1 ± 0.3	3.4 ± 0.3	81.1 ± 24.8	67.1 ± 10.4	25.4 ± 9.5	19.0 ± 14.6
10/5	13.6 ± 5.8	20.5 ± 7.2	2.2 ± 0.3	2.1 ± 0.1	75.6 ± 25.7	55.9 ± 25.6	4.4 ± 0.7	3.4 ± 1.3
10/12	4.0 ± 1.1	3.5 ± 0.6	2.3 ± 0.0	2.1 ± 0.4	8.9 ± 8.7	7.2 ± 3.5	2.3 ± 0.2	2.4 ± 0.3
11/7	0.4 ± 0.1	0.4 ± 0.1	2.6 ± 0.3	2.3 ± 0.4	0.2 ± 0.0	0.4 ± 0.2	1.6 ± 0.2	1.5 ± 0.2
11/30	0.2 ± 0.1	0.5 ± 0.1	2.8 ± 0.2	2.9 ± 0.4	0.2 ± 0.1	0.6 ± 0.2	1.7 ± 0.4	1.9 ± 0.2
12/7	0.3 ± 0.1	0.6 ± 0.2	2.2 ± 0.2	2.2 ± 0.4	0.3 ± 0.1	0.6 ± 0.3	1.5 ± 0.2	1.4 ± 0.2
12/12	0.7 ± 0.1	1.4 ± 1.6	2.4 ± 0.3	2.5 ± 0.3	2.2 ± 1.7	1.5 ± 0.2	1.8 ± 0.2	1.5 ± 0.2

Mean ± SD

Date of fertilizer application: 4/12, 9/13

Date of harvest (crop residue input): 6/26, 12/10

Date of incorporation of residue: 7/6, 12/19

Table S3. Seasonal change of soil inorganic N in 2013

Date	Andosol				Fluvisol			
	NO_3^- (μgN g soil^{-1})		NH_4^+ (μgN g soil^{-1})		NO_3^- (μgN g soil^{-1})		NH_4^+ (μgN g soil^{-1})	
(m/d)	NR	WR	NR	WR	NR	WR	NR	WR
Spring potato								
3/19	3.9 ± 0.8	30.3 ± 9.4	2.0 ± 0.3	2.1 ± 0.0	10.5 ± 4.7	41.1 ± 7.3	2.1 ± 0.2	2.9 ± 0.5
3/29	69.5 ± 4.8	119.4 ± 10.9	105.9 ± 60.8	138.1 ± 22.0	39.0 ± 3.7	83.7 ± 10.7	147.9 ± 52.7	132.5 ± 10.2
4/1	87.8 ± 4.0	118.5 ± 12.5	106.1 ± 6.9	93.1 ± 45.1	48.5 ± 4.0	103.8 ± 6.3	106.5 ± 5.7	127.5 ± 30.3
4/5	63.3 ± 23.1	66.3 ± 27.9	40.2 ± 26.7	14.3 ± 8.1	45.4 ± 4.4	50.5 ± 7.1	90.1 ± 24.2	34.7 ± 10.2
4/8	34.8 ± 16.2	20.8 ± 14.5	6.4 ± 4.1	3.1 ± 0.2	34.3 ± 9.0	25.6 ± 7.8	28.4 ± 27.9	6.2 ± 1.7
4/12	65.9 ± 19.4	24.2 ± 13.9	3.6 ± 1.6	3.5 ± 0.5	69.2 ± 26.5	44.8 ± 17.7	9.8 ± 5.8	3.4 ± 0.5
4/15	48.4 ± 18.1	33.5 ± 29.9	2.5 ± 0.3	2.5 ± 0.4	60.9 ± 11.6	58.7 ± 22.9	8.3 ± 5.8	3.9 ± 1.5
4/22	10.3 ± 6.7	12.1 ± 7.9	5.0 ± 2.3	3.8 ± 0.7	14.2 ± 4.6	13.1 ± 4.9	4.9 ± 1.5	3.8 ± 1.1
4/26	4.0 ± 1.8	7.0 ± 6.1	2.6 ± 0.2	2.8 ± 0.1	8.5 ± 5.3	7.0 ± 2.1	2.7 ± 0.6	2.5 ± 0.1
5/2	23.3 ± 5.8	13.9 ± 7.1	2.4 ± 0.4	2.9 ± 0.2	13.2 ± 8.9	20.3 ± 5.7	2.5 ± 0.3	2.4 ± 0.1
5/10	30.1 ± 14.9	25.3 ± 18.7	1.5 ± 0.2	1.6 ± 0.8	32.5 ± 28.3	29.0 ± 20.5	1.6 ± 0.3	1.6 ± 0.3
5/22	4.1 0.9	6.2 0.4	1.8 0.6	1.6 0.1	4.8 2.4	4.7 2.4	1.3 0.5	1.3 0.3
6/3	7.3 ± 6.7	20.2 ± 19.1	1.6 ± 0.5	1.6 ± 0.6	4.7 ± 4.2	8.4 ± 2.9	1.6 ± 0.5	1.4 ± 0.4
6/17	4.6 ± 0.4	12.1 ± 5.3	2.2 ± 0.3	3.4 ± 0.8	2.1 ± 0.6	10.9 ± 4.4	1.9 ± 0.3	6.1 ± 2.6
6/24	2.7 ± 0.6	8.3 ± 2.9	2.1 ± 0.3	2.4 ± 0.6	2.6 ± 0.6	11.8 ± 8.1	1.5 ± 0.1	3.1 ± 2.2
Autumn potato								
8/26	37.7 ± 12.0	75.7 ± 22.0	5.9 ± 0.8	5.7 ± 1.9	31.4 ± 15.1	47.9 ± 8.9	6.7 ± 1.8	7.5 ± 1.1
9/2	125.2 ± 6.9	158.0 ± 10.5	158.5 ± 39.0	97.8 ± 43.9	89.3 ± 11.2	121.8 ± 22.2	109.0 ± 8.5	119.3 ± 47.5
9/4	39.6 ± 23.1	43.1 ± 17.4	69.1 ± 37.0	55.4 ± 42.7	14.9 ± 3.3	18.4 ± 5.9	122.6 ± 12.7	85.7 ± 41.7
9/9	58.9 ± 4.6	55.3 ± 26.7	5.3 ± 0.2	28.5 ± 40.5	54.9 ± 26.3	49.1 ± 13.9	35.0 ± 12.9	24.4 ± 15.1
9/11	61.4 ± 15.7	48.4 ± 5.8	3.5 ± 0.6	3.6 ± 0.4	65.7 ± 16.6	58.6 ± 16.3	21.2 ± 1.5	10.3 ± 4.5
9/18	4.3 ± 0.8	5.6 ± 1.2	3.2 ± 0.1	3.4 ± 0.2	7.6 ± 2.0	5.8 ± 0.6	6.1 ± 2.2	4.7 ± 1.1
9/20	8.3 ± 2.5	8.5 ± 1.4	3.2 ± 0.3	3.3 ± 0.5	15.4 ± 5.5	12.6 ± 3.6	5.3 ± 1.0	4.4 ± 0.6
9/27	14.1 ± 5.4	12.8 ± 0.9	3.4 ± 0.2	3.4 ± 0.2	19.1 ± 3.7	26.3 ± 18.5	2.7 ± 0.4	3.6 ± 1.3
10/4	3.1 ± 0.9	3.5 ± 0.8	2.2 ± 0.4	2.1 ± 0.2	3.8 ± 0.9	4.7 ± 1.1	1.6 ± 0.3	2.1 ± 0.4
11/1	2.0 ± 0.5	2.6 ± 0.8	2.4 ± 0.2	2.7 ± 0.2	3.6 ± 1.5	3.2 ± 1.0	2.5 ± 0.2	2.4 ± 0.1
11/8	2.7 ± 0.9	4.4 ± 2.6	2.3 ± 0.2	2.4 ± 0.2	2.6 ± 1.1	5.6 ± 1.4	2.3 ± 0.1	2.6 ± 0.2
11/22	4.7 ± 0.6	10.4 ± 3.5	2.5 ± 0.2	2.5 ± 0.3	7.2 ± 0.8	20.3 ± 8.3	2.2 ± 0.1	3.3 ± 0.3

Mean ± SD

Date of fertilizer application: 3/26, 8/27

Date of haulm cut (crop residue input): 6/7, 10/31

Date of harvest (incorporation of residue): 6/21, 11/11

Table S4. Cumulative N_2O emission in 2012

			After fertilizer application			After residue input		
Soil type	Treatment	Cumulative emission (kgN ha^{-1})	Emission after fertilizer application (kgN ha^{-1})	Percentage to cumulative emission (%)	fertilizer N emitted as N_2O-N# (%)	Emission after residue input (kgN ha^{-1})	Percentage to cumulative emission (%)	Crop residue induced N_2O emission factor \$ (%)
Spring Cabbage		(Jan. 1 to Aug. 31) (244 days)	(April 12 to May 11) (30 days)			(June 26 to July 25) (30 days)		
Andosol	WR	2.02 ± 0.12	0.44 ± 0.08	(22)	0.08 ± 0.01	1.26 ± 0.17	(62)	3.96 ± 0.56
Andosol	NR	0.79 ± 0.07	0.42 ± 0.06	(53)	0.08 ± 0.08	0.05 ± 0.01	(7)	
Fluvisol	WR	2.78 ± 0.12	0.27 ± 0.01	(10)	0.05 ± 0.00	2.05 ± 0.71	(74)	7.50 ± 2.81
Fluvisol	NR	0.80 ± 0.06	0.22 ± 0.04	(27)	0.04 ± 0.01	0.15 ± 0.02	(19)	
Statistical	treatment	***	ns		ns	***		-
Significance	soil	*	**		***	***		ns
	treatment*soil	*	ns		ns	ns		-
Autumn Cabbage		(Sep. 1 to Dec. 31) (122 days)	(Sep. 13 to Oct. 12) (30 days)			(Dec. 10 to Dec. 31) (23 days)		
Andosol	WR	2.77 ± 0.28	2.56 ± 0.24	(93)	0.49 ± 0.05	0.01 ± 0.00	(1)	0.09 ± 0.02
Andosol	NR	2.05 ± 1.02	1.88 ± 0.93	(92)	0.36 ± 0.18	0.01 ± 0.00	(0)	
Fluvisol	WR	1.44 ± 0.47	0.99 ± 0.28	(69)	0.19 ± 0.04	0.06 ± 0.03	(4)	0.24 ± 0.22
Fluvisol	NR	1.41 ± 0.53	0.95 ± 0.28	(67)	0.18 ± 0.04	0.03 ± 0.01	(2)	
Statistical	treatment	ns	ns		ns	*		-
Significance	soil	ns	*		**	***		ns
	treatment*soil	ns	ns		ns	ns		-
Annual emission		(Jan. 1 to Dec. 31) (366days)	(April 12 to May 11 and Sep. 13 to Oct. 12) (60 days)			(June 26 to July 25 and Dec. 10 to Dec. 31) (53 days)		
Andosol	WR	4.79 ± 0.31	3.01 ± 0.30	(63)	0.29 ± 0.03	1.27 ± 0.17	(27)	3.02 ± 0.42
Andosol	NR	2.84 ± 1.01	2.30 ± 0.92	(81)	0.22 ± 0.09	0.06 ± 0.01	(2)	
Fluvisol	WR	4.22 ± 0.68	1.26 ± 0.24	(30)	0.12 ± 0.02	2.10 ± 0.69	(50)	5.37 ± 1.93
Fluvisol	NR	2.22 ± 0.49	1.16 ± 0.23	(52)	0.11 ± 0.02	0.18 ± 0.03	(8)	
Statistical	treatment	**	ns		ns	***		-
Significance	soil	ns	**		**	ns		ns
	treatment*soil	ns	ns		ns	ns		-

Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.

For statistical analysis, log-transformed data were tested with 2way ANOVA, except for emission factor. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

N emitted as N_2O: (N_2O-N)/(N applied as fertilizer)*100; note that zero-N control was not used.

\$Crop residue induced N_2O emission factor: ((N_2O-N from WR)- (N_2O-N from NR))/(residue N)*100. For statistical analysis of N_2O emission factor, t-test was used.

Table S5. Cumulative N_2O emission in 2013

Soil type	Treatment	Cumulative emission (kgN ha^{-1})	After fertilizer application: Emission after fertilizer application (kgN ha^{-1})	After fertilizer application: Percentage to cumulative emission (%)	After fertilizer application: fertilizer N emitted as N_2O-N# (%)	After residue input: Emission after residue input (kgN ha^{-1})	After residue input: Percentage to cumulative emission (%)	After residue input: Crop residue induced N_2O emission factor $ (%)
Spring Potato		(Jan. 1 to Aug. 26) (236 days)	(March 26 to April 24) (30 days)			(June 7 to July 6) (30 days)		
Andosol	WR	2.29 ± 1.11	0.88 ± 0.61	(39)	0.35 ± 0.24	1.06 ± 0.48	(46)	14.6 ± 6.8
Andosol	NR	0.42 ± 0.12	0.27 ± 0.10	(64)	0.10 ± 0.04	0.03 ± 0.01	(6)	
Fluvisol	WR	2.02 ± 0.37	0.19 ± 0.02	(10)	0.08 ± 0.01	1.10 ± 0.22	(54)	12.8 ± 2.8
Fluvisol	NR	0.72 ± 0.07	0.20 ± 0.02	(27)	0.08 ± 0.01	0.07 ± 0.02	(10)	
Statistical Significance	treatment	***	ns		ns	***		-
	soil	ns	*		*	*		ns
	treatment*soil	ns	ns		ns	ns		-
Autumn Potato		(Aug. 27 to Dec. 31) (127 days)	(Aug. 27 to Sep. 25) (30 days)			(Oct. 31 to Nov. 29) (23 days)		
Andosol	WR	1.07 ± 0.29	0.75 ± 0.16	(70)	0.29 ± 0.06	0.20 ± 0.11	(19)	1.78 ± 1.30
Andosol	NR	1.03 ± 0.19	0.84 ± 0.22	(82)	0.33 ± 0.09	0.05 ± 0.01	(5)	
Fluvisol	WR	1.37 ± 0.21	0.80 ± 0.22	(58)	0.31 ± 0.09	0.23 ± 0.05	(17)	0.00 ± 0.44
Fluvisol	NR	1.27 ± 0.32	0.67 ± 0.22	(53)	0.26 ± 0.08	0.31 ± 0.09	(24)	
Statistical Significance	treatment	*	ns		ns	***		-
	soil	**	ns		ns	ns		ns
	treatment*soil	ns	ns		ns	ns		-
Annual emission		(Jan. 1 to Dec. 31, 2012) (365 days)	(March 26 to April 24 and Aug. 27 to Sep. 25) (60 days)			(June 7 to July 6 and Oct. 31 to Nov. 29) (53 days)		
Andosol	WR	3.36 ± 0.96	1.63 ± 0.51	(48)	0.32 ± 0.10	1.26 ± 0.44	(38)	7.51 ± 2.78
Andosol	NR	1.45 ± 0.32	1.10 ± 0.32	(76)	0.22 ± 0.06	0.07 ± 0.01	(5)	
Fluvisol	WR	3.41 ± 0.57	0.99 ± 0.24	(29)	0.19 ± 0.05	1.33 ± 0.18	(39)	5.10 ± 0.99
Fluvisol	NR	2.01 ± 0.25	0.87 ± 0.24	(43)	0.17 ± 0.05	0.38 ± 0.10	(19)	
Statistical Significance	treatment	***	ns		ns	***		-
	soil	ns	ns		ns	***		ns
	treatment*soil	ns	ns		ns	**		-

Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.

For statistical analysis, log-transformed data were tested with 2way ANOVA, except for emission factor. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

N emitted as N_2O: (N_2O-N)/(N applied as fertilizer)*100; note that zero-N control was not used.

$ Crop residue induced N_2O emission factor: ((N_2O-N from WR)- (N_2O-N from NR))/(residue N)*100. For statistical analysis of N_2O emission factor, t-test was used.

Table S6. Pearson's correlation coefficients between soil environmental factors and daily N_2O and NO fluxes from cabbage fields in 2012

	N_2O					NO				
	Annual	After fertilizaer		After residue		Annual	After fertilizaer		After residue	
		Spring	Autumn	Summer	Winter		Spring	Autumn	Summer	Winter
Andosol, NR										
Temprature	0.256**	-0.153	0.182	0.093	0.170	0.361**	-0.151	0.796**	0.289	-0.49*
WFPS	0.654**	0.741**	0.802**	0.660**	0.370*	0.376**	0.739**	0.082	0.345	0.069
NO_3^-	0.268	0.973*	-0.097	-0.924*	-0.996	0.703**	0.974*	0.917*	0.491	0.992
NH_4^+	0.020	0.233	-0.402	0.405	0.243	0.273	0.233	0.387	0.138	-0.208
Andosol, WR										
Temprature	0.294**	-0.063	0.026	-0.039	0.151	0.300**	-0.064	0.683**	0.317	-0.344
WFPS	0.527**	0.764**	0.687**	0.778**	0.624**	0.373**	0.766**	0.008	-0.480**	0.017
NO_3^-	0.090	0.901	-0.298	-0.033	0.359	0.495*	0.899	0.448	0.434	-0.998**
NH_4^+	-0.168	0.022	-0.545	0.250	0.763	0.201	0.016	0.227	-0.094	0.267
Fluvisol, NR										
Temprature	0.338**	0.619**	-0.457*	-0.446*	0.460**	0.348**	0.554**	0.049	-0.024	0.481**
WFPS	0.602**	0.215	0.349	-0.088	0.481**	0.450**	-0.232	0.107	-0.392*	0.559**
NO_3^-	0.621**	0.955*	0.003	-0.788	-0.811	0.889**	0.905	0.766	0.857	-0.991
NH_4^+	0.020	-0.964*	-0.431	-0.114	-0.334	0.046	-0.941	-0.456	0.917*	-0.739
Fluvisol, WR										
Temprature	0.254**	0.594**	-0.131	-0.087	0.232	0.611**	0.577**	0.505**	0.163	0.419*
WFPS	0.262**	0.200	0.597**	0.805**	0.483**	0.311**	-0.157	0.366	0.579**	0.592**
NO_3^-	0.077	0.997**	-0.057	-0.305	-0.977	0.710**	0.809	0.808	0.071	-0.959
NH_4^+	-0.222	-0.995**	-0.199	0.569	0.516	0.139	-0.795	0.218	0.612	0.575

*$p < 0.05$, **$p < 0.01$.

Table S7. Pearson's correlation coefficients between soil environmental factors and daily N_2O and NO fluxes from potato fields in 2013

	N_2O					NO				
	Annual	After fertilizaer		After residue		Annual	After fertilizaer		After residue	
		Spring	Autumn	Summer	Winter		Spring	Autumn	Summer	Winter
<u>Andosol, NR</u>										
Temprature	0.228**	0.085	0.219	-0.264	0.767**	0.189**	-0.166	0.605**	0.284	-0.468*
WFPS	0.387**	0.076	0.848**	-0.235	0.860**	-0.033	-0.520*	-0.018	0.598**	-0.533*
NO_3^-	0.530**	0.238	0.473	-0.519	-0.676	0.634**	-0.243	0.764*	-0.763	-0.567
NH_4^+	0.671**	0.971**	0.425	-0.434	0.664	0.881**	0.959**	0.766*	-0.126	-1.000**
<u>Andosol, WR</u>										
Temprature	0.167**	0.308	0.339	-0.134	0.712**	0.093	-0.166	0.666**	0.061	-0.385*
WFPS	0.179**	0.106	0.789**	0.684**	0.701**	-0.042	-0.655**	0.129	0.415*	-0.388*
NO_3^-	0.339	0.657	0.368	0.820	-0.533	0.859**	0.838*	0.900**	0.698	-0.169
NH_4^+	0.408*	0.451	0.439	0.950	-0.665	0.799**	0.932**	0.875**	0.992	0.433
<u>Fluvisol, NR</u>										
Temprature	0.361**	0.381*	-0.004	0.015	0.453*	0.339**	0.207	0.204	0.311	-0.260
WFPS	0.652**	0.446*	0.858**	0.580**	0.672**	0.173**	-0.013	0.049	-0.632**	-0.680**
NO_3^-	0.199	0.244	-0.179	-0.893	-0.741	0.705**	0.245	0.699	-0.215	-0.180
NH_4^+	0.343	0.280	0.361	0.864	0.151	0.691**	0.865*	0.141	0.936	-0.481
<u>Fluvisol, WR</u>										
Temprature	0.215**	0.290	-0.050	-0.189	-0.116	0.469**	0.074	0.208	0.066	-0.259
WFPS	0.303**	0.512**	0.847**	0.710**	-0.632*	0.177**	-0.046	-0.032	0.630**	-0.746**
NO_3^-	-0.015	0.236	-0.058	0.912	0.958	0.756**	0.770*	0.687	0.855	0.874
NH_4^+	0.052	0.332	-0.127	0.875	0.957	0.530**	0.555	0.150	0.928	0.873

*$p < 0.05$, **$p < 0.01$.

Table S8. Pearson's correlation coefficients between temperature and daily N_2O and NO fluxes after the input of crop residues in the WR treatment. Data include summer and winter.

	N_2O		NO	
	Cabbages, 2012	Potatoes, 2013	Cabbages, 2012	Potatoes, 2013
Andosol				
Temperature	0.386^{**}	0.305^{*}	0.722^{**}	0.465^{**}
Fluvisol				
Temperature	0.413^{**}	0.257^{*}	0.683^{**}	0.406^{**}

*$p < 0.05$, **$p < 0.01$.

Table S9. Cumulative NO emission in 2012

Soil type	Treatment	Cumulative emission (kgN ha^{-1})	After fertilizer application: Emission after fertilizer application (kgN ha^{-1})	After fertilizer application: percentage to cumulative emission (%)	After fertilizer application: fertilizer N emitted as NO# (%)	After residue input: Emission after residue input (kgN ha^{-1})	After residue input: percentage to cumulative emission (%)	After residue input: Crop residue induced NO emission factor $ (%)
<u>Spring Cabbage</u>		(Jan. 1 to Aug. 31) (244 days)	(April 12 to May 11) (30 days)			(June 26 to July 25) (30 days)		
Andosol	WR	0.98 ± 0.17	0.45 ± 0.08	(46)	0.09 ± 0.01	0.08 ± 0.03	(8)	0.00 ± 0.11
Andosol	NR	1.29 ± 0.16	0.42 ± 0.06	(33)	0.08 ± 0.01	0.33 ± 0.10	(26)	
Fluvisol	WR	0.29 ± 0.02	0.01 ± 0.00	(3)	0.002 ± 0.001	0.06 ± 0.00	(20)	0.04 ± 0.02
Fluvisol	NR	0.23 ± 0.06	0.01 ± 0.00	(5)	0.002 ± 0.001	0.05 ± 0.01	(22)	
Statistical	treatment	ns	ns		ns	*		-
Significance	soil	***	***		***	**		***
	treatment*soil	ns	ns		ns	**		-
<u>Autumn Cabbage</u>		(Sep. 1 to Dec. 31) (122 days)	(Sep. 13 to Oct. 12) (30 days)			(Dec. 10 to Dec. 31) (23 days)		
Andosol	WR	4.12 ± 0.13	3.84 ± 0.12	(93)	0.74 ± 0.02	-0.004 ± 0.004	(0)	0.00 ± 0.04
Andosol	NR	2.97 ± 0.76	2.72 ± 0.75	(92)	0.52 ± 0.14	-0.003 ± 0.005	(0)	
Fluvisol	WR	0.88 ± 0.04	0.20 ± 0.06	(23)	0.04 ± 0.01	0.31 ± 0.05	(35)	0.00 ± 0.47
Fluvisol	NR	0.56 ± 0.17	0.03 ± 0.00	(5)	0.01 ± 0.00	0.37 ± 0.16	(67)	
Statistical	treatment	*	***		***	ns		-
Significance	soil	***	***		***	***		ns
	treatment*soil	ns	**		***	ns		-
Annual emission		(Jan. 1 to Dec. 31) (366days)	(April 12 to May 11 and Sep. 13 to Oct. 12) (60 days)			(June 26 to July 25 and Dec. 10 to Dec. 31) (53 days)		
Andosol	WR	5.11 ± 0.29	4.29 ± 0.19	(84)	0.41 ± 0.02	0.08 ± 0.03	(2)	0.00 ± 0.08
Andosol	NR	4.26 ± 0.82	3.14 ± 0.81	(74)	0.30 ± 0.08	0.33 ± 0.11	(8)	
Fluvisol	WR	1.17 ± 0.06	0.21 ± 0.1	(18)	0.020 ± 0.006	0.37 ± 0.05	(31)	0.00 ± 0.15
Fluvisol	NR	0.79 ± 0.17	0.04 ± 0.0	(5)	0.004 ± 0.000	0.42 ± 0.16	(53)	
Statistical	treatment	*	***		***	ns		-
Significance	soil	***	***		***	ns		**
	treatment*soil	ns	**		**	ns		-

Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.

For statistical analysis, log-transformed data were tested with 2way ANOVA, except for emission factor. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

N emitted as NO: (NO-N)/(N applied as fertilizer)*100; note that zero-N control was not used.

$ Crop residue induced NO emission factor: ((N_2O-N from WR)- (NO-N from NR))/(residue N)*100. For statistical analysis of NO emission factor, t-test was used.

Table S10. Cumulative NO emission in 2013

Soil type	Treatment	Cumulative emission (kgN ha^{-1})	After fertilizer application: Emission after fertilizer application (kgN ha^{-1})	After fertilizer application: percentage to cumulative emission (%)	After fertilizer application: fertilizer N emitted as NO# (%)	After residue input: Emission after residue input (kgN ha^{-1})	After residue input: percentage to cumulative emission (%)	Crop residue induced NO emission factor $ (%)
Spring Potato		(Jan. 1 to Aug. 26) (236 days)	(March 26 to April 24) (30 days)			(June 7 to July 6) (30 days)		
Andosol	WR	3.36 ± 1.29	1.66 ± 1.11	(49)	0.65 ± 0.43	0.34 ± 0.13	(10)	3.02 ± 1.79
Andosol	NR	1.96 ± 0.50	0.44 ± 0.41	(22)	0.17 ± 0.16	0.13 ± 0.03	(6)	
Fluvisol	WR	1.84 ± 0.39	0.40 ± 0.06	(22)	0.16 ± 0.02	0.43 ± 0.15	(23)	4.70 ± 1.84
Fluvisol	NR	0.98 ± 0.13	0.41 ± 0.03	(42)	0.16 ± 0.01	0.05 ± 0.02	(5)	
Statistical Significance	treatment	ns	ns		ns	ns		-
	soil	ns	ns		ns	*		ns
	treatment*soil	ns	ns		ns	*		-
Autumn Potato		(Aug. 27 to Dec. 31) (127 days)	(Aug. 27 to Sep. 25) (30 days)			(Oct. 31 to Nov. 29) (23 days)		
Andosol	WR	1.51 ± 0.29	1.47 ± 0.31	(98)	0.58 ± 0.12	0.000 ± 0.000	(0)	0.00 ± 0.00
Andosol	NR	1.67 ± 0.15	1.63 ± 0.16	(98)	0.64 ± 0.06	0.000 ± 0.000	(0)	
Fluvisol	WR	1.14 ± 0.29	0.87 ± 0.22	(76)	0.34 ± 0.09	0.078 ± 0.018	(7)	0.74 ± 0.17
Fluvisol	NR	0.84 ± 0.60	0.73 ± 0.50	(86)	0.28 ± 0.20	0.000 ± 0.004	(0)	
Statistical Significance	treatment	ns	ns		ns	***		-
	soil	*	*		*	***		***
	treatment*soil	ns	ns		ns	*		-
Annual emission		(Jan. 1 to Dec. 31, 2012) (366days)	(March 26 to April 24 and Aug. 27 to Sep. 25) (60 days)			(June 7 to July 6 and Oct. 31 to Nov. 29) (53 days)		
Andosol	WR	4.98 ± 1.38	3.13 ± 1.24	(63)	0.61 ± 0.24	0.34 ± 0.13	(7)	1.35 ± 0.80
Andosol	NR	3.77 ± 0.61	2.07 ± 0.55	(55)	0.40 ± 0.11	0.13 ± 0.03	(3)	
Fluvisol	WR	3.00 ± 0.68	1.27 ± 0.27	(42)	0.25 ± 0.05	0.50 ± 0.16	(17)	2.44 ± 0.86
Fluvisol	NR	1.83 ± 0.52	1.14 ± 0.50	(62)	0.22 ± 0.10	0.05 ± 0.02	(3)	
Statistical Significance	treatment	ns	ns		ns	***		-
	soil	**	*		*	ns		ns
	treatment*soil	ns	ns		ns	*		-

Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.

For statistical analysis, log-transformed data were tested with 2way ANOVA, except for emission factor. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

N emitted as NO: (NO-N)/(N applied as fertilizer)*100; note that zero-N control was not used.

$ Crop residue induced NO emission factor: ((NO-N from WR)- (NO-N from NR))/(residue N)*100. For statistical analysis of NO emission factor, t-test was used.

Table S11. Cumulative CH_4 emission in 2012

Soil type	Treatment	Total CH_4 emission (kg ha^{-1})	CH_4 emission after fertilizer application (kg ha^{-1})	CH_4 emission After harvest (kg ha^{-1})
Spring Cabbage		(Jan. 1 to Aug. 31) (244 days)	(April 12 to May 11) (30 days)	(June 26 to July 25) (30 days)
Andosol	WR	-2.65 ± 0.37	-0.21 ± 0.04	-0.30 ± 0.04
Andosol	NR	-3.27 ± 0.23	-0.28 ± 0.02	-0.44 ± 0.03
Fluvisol	WR	-0.26 ± 0.07	-0.04 ± 0.00	-0.05 ± 0.02
Fluvisol	NR	-0.26 ± 0.03	-0.04 ± 0.00	-0.06 ± 0.01
Statistical Significance	treatment	ns	ns	ns
	soil	***	***	***
	treatment*soil	ns	ns	ns
Autumn Cabbage		(Sep. 1 to Dec. 31) (122 days)	(Sep. 13 to Oct. 12) (30 days)	(Dec. 10 to Dec. 31) (23 days)
Andosol	WR	-1.01 ± 0.16	-0.19 ± 0.02	-0.16 ± 0.02
Andosol	NR	-1.30 ± 0.07	-0.24 ± 0.01	-0.22 ± 0.03
Fluvisol	WR	-0.17 ± 0.02	-0.04 ± 0.02	-0.03 ± 0.01
Fluvisol	NR	-0.16 ± 0.03	-0.02 ± 0.01	-0.04 ± 0.00
Statistical Significance	treatment	ns	ns	ns
	soil	***	***	***
	treatment*soil	ns	ns	ns
Annual emission		(Jan. 1 to Dec. 31) (366days)	(April 12 to May 11) (Sep. 13 to Oct. 12) (60 days)	
Andosol	WR	-3.66 ± 0.52	-0.40 ± 0.06	-0.46 ± 0.07
Andosol	NR	-4.59 ± 0.29	-0.52 ± 0.03	-0.65 ± 0.05
Fluvisol	WR	-0.43 ± 0.08	-0.07 ± 0.02	-0.08 ± 0.01
Fluvisol	NR	-0.42 ± 0.06	-0.06 ± 0.01	-0.10 ± 0.01
Statistical Significance	treatment	ns	ns	ns
	soil	***	***	***
	treatment*soil	ns	ns	ns

Negative CH_4 emission values indicate uptake by the soil. Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.
For statistical analysis, log-transformed data were tested with 2way ANOVA.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

Table S12. Cumulative CH_4 emission in 2013

Soil type	Treatment	Total CH_4 emission (kg ha^{-1})	CH_4 emission after fertilizer application (kg ha^{-1})	CH_4 emission After harvest (kg ha^{-1})
Soil type	Treatment	(Jan. 1 to Aug. 31) (244 days)	(April 12 to May 11) (30 days)	(June 26 to July 25) (30 days)
Spring Potato				
Andosol	WR	-1.35 ± 0.04	-0.15 ± 0.02	-0.26 ± 0.02
Andosol	NR	-1.33 ± 0.46	-0.13 ± 0.06	-0.27 ± 0.09
Fluvisol	WR	-0.20 ± 0.06	-0.03 ± 0.00	-0.03 ± 0.02
Fluvisol	NR	-0.19 ± 0.05	-0.03 ± 0.00	-0.04 ± 0.02
Statistical	treatment	ns	ns	ns
Significance	soil	***	***	***
	treatment*soil	ns	ns	ns
Autumn Potato		(Sep. 1 to Dec. 31) (122 days)	(Sep. 13 to Oct. 12) (30 days)	(Dec. 10 to Dec. 31) (23 days)
Andosol	WR	-1.20 ± 0.08	-0.28 ± 0.03	-0.29 ± 0.01
Andosol	NR	-1.35 ± 0.02	-0.32 ± 0.03	-0.33 ± 0.01
Fluvisol	WR	-0.32 ± 0.01	-0.03 ± 0.01	-0.10 ± 0.01
Fluvisol	NR	-0.34 ± 0.06	-0.02 ± 0.02	-0.11 ± 0.01
Statistical	treatment	ns	ns	ns
Significance	soil	***	***	***
	treatment*soil	ns	ns	ns
Annual emission		(Jan. 1 to Dec. 31) (365 days)	(April 12 to May 11 & Sep. 13 to Oct. 12) (60 days)	(June 26 to July 25 & Dec. 10 to Dec. 31) (53 days)
Andosol	WR	-2.56 ± 0.04	-0.43 ± 0.02	-0.54 ± 0.01
Andosol	NR	-2.69 ± 0.44	-0.45 ± 0.09	-0.60 ± 0.08
Fluvisol	WR	-0.53 ± 0.06	-0.07 ± 0.01	-0.13 ± 0.02
Fluvisol	NR	-0.52 ± 0.11	-0.05 ± 0.02	-0.14 ± 0.03
Statistical	treatment	ns	ns	ns
Significance	soil	***	***	***
	treatment*soil	ns	ns	ns

Negative CH_4 emission values indicate uptake by the soil. Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue.
For statistical analysis, log-transformed data were tested with 2way ANOVA.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns: not significant

Table S13. Daily CH_4 flux in 2012

Soil type	Treatment	Daily CH_4 flux after fertilizer application ($mg\ m^{-2}\ d^{-1}$)	Daily CH_4 flux except period after fertilizer ($mg\ m^{-2}\ d^{-1}$)
		(April 12 to May 11 & Sep. 13 to Oct. 12) (60 days)	(306 days)
Andosol	WR	-1.32 ± 0.21	-10.9 ± 1.5
Andosol	NR	-1.73 ± 0.09	-13.6 ± 0.9
Fluvisol	WR	-0.07 ± 0.02	-0.36 ± 0.06
Fluvisol	NR	-0.06 ± 0.01	-0.36 ± 0.05
Statistical Significance	residue	ns	
	soil	***	
	fertilizer#	***	
	treatment*soil	ns	
	treatment*fertilizer	ns	
	soil*fertilizer	*	
	treatment*soil*fertilizer	ns	

Negative CH_4 emission values indicate uptake by the soil. Mean ± standard deviation of 3 replicates. Treatments: WR: with crop residue, NR: without crop residue

For statistical analysis, log-transformed data were tested with 3-way ANOVA.

#fertilizer: comparison between "after fertilizer" and "except period after fertilizer".

Table S14. Daily CH_4 flux in 2013

Soil type	Treatment	Daily CH_4 flux after fertilizer application ($mg\ m^{-2}\ d^{-1}$)			Daily CH_4 flux except period after fertilizer ($mg\ m^{-2}\ d^{-1}$)		
		(April 12 to May 11 & Sep. 13 to Oct. 12) (60 days)			(305 days)		
Andosol	WR	-0.43	±	0.02	-2.1	±	0.0
Andosol	NR	-0.45	±	0.09	-2.2	±	0.3
Fluvisol	WR	-0.07	±	0.01	-0.46	±	0.05
Fluvisol	NR	-0.05	±	0.02	-0.47	±	0.09
Statistical	residue			ns			
Sgnificance	soil			***			
	fertilizer#			***			
	treatment*soil			ns			
	treatment*fertilizer			ns			
	soil*fertilizer			***			
	treatment*soil*fertilizer			ns			

For statistical analysis, log-transformed data were tested with 3-way ANOVA.
#fertilizer: comparison between "after fertilizer" and "except period after fertilizer"

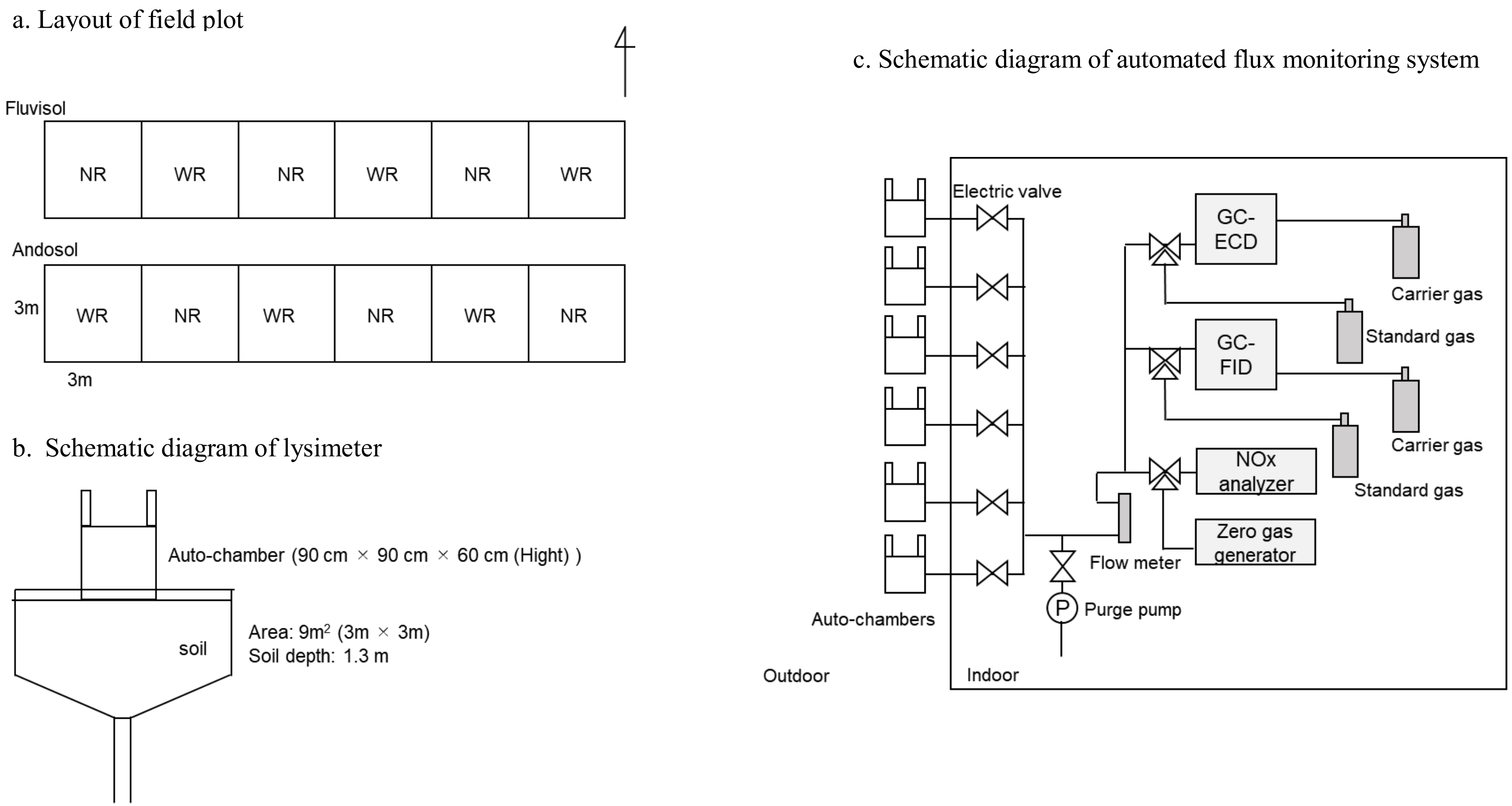

Fig. S1 Experimental design

(a) Layout of field plot; NR: without crop residue, WR: with crop residue. (b) Schematic diagram of lysimeter. (c) Two sets of auto-monitoring systems were used for each soil type (Andosol and Fluvisol). GC-ECD: gas chromatograph with electron capture detector, GC-FID: gas chromatograph with flame ionization detector