

Surface application of fertilizers and residue biochar on N₂O emission from Japanese pear orchard soil

AUNG ZAW OO^{1,5,*}, TAKERU GONAI^{2,*}, SHIGETO SUDO¹, KHIN THUZAR WIN³, AKIRA SHIBATA⁴

¹*Institute for Agro-Environmental Science, National Agriculture and Food Research Organization, Tsukuba, Ibaraki, Japan*

²*Horticultural Institute, Ibaraki Agricultural Center, Kasama, Ibaraki, Japan*

³*Central Regional Agricultural Research Center, National Agriculture and Food Research Organization, Tsukuba, Japan*

⁴*Ritsumeikan University OIC Research Organization, Ibaraki, Osaka, Japan*

⁵*Natural Science Research Unit, Tokyo Gakugei University, Koganei, Tokyo, Japan*

*Corresponding authors: aungzawo@gmail.com; t.gounai@pref.ibaraki.lg.jp

ABSTRACT

Oo A.Z., Gonai T., Sudo S., Win K.T., Shibata A. (2018): Surface application of fertilizers and residue biochar on N₂O emission from Japanese pear orchard soil. *Plant Soil Environ.*, 64: 597–604.

This study investigated soil N₂O emissions following the application of fertilizers and pruning residue biochar on the soil surface of the Japanese pear orchard. Completely randomized design was laid out with four treatments: (1) control (unfertilized); (2) pig manure 300 kg N/ha and ammonium sulfate 200 kg N/ha with no biochar (F + BC0); (3) the same amount of manure and nitrogen (N) fertilizer with 2 t/ha biochar (F + BC2), and (4) with 10 t/ha biochar (F + BC10). The results showed that high N₂O fluxes were observed after fertilization. Soil temperature and moisture were major controlling factors for N₂O emission from the orchard soil. The lowest cumulative N₂O emission (0.46 kg N/ha) was observed in the unfertilized control. Application of manure and N fertilizer significantly increased cumulative N₂O emission compared to unfertilized control. Surface application of biochar (1.68 and 1.77 kg N/ha in F + BC2 and F + BC10, respectively) had no effect on soil N₂O emission compared to F + BC0 (1.68 kg N/ha). Our results indicated that biochar pyrolyzed from orchard pruning residues can be returned to orchard soil as surface application without affecting soil N₂O emissions.

Keywords: charcoal; greenhouse gas; no-tilled soil; *Pyrus pyrifolia*; residue management

The Japanese pear is widely cultivated from the northern (Hokkaido region) to the southern (Kyushu region) regions of Japan. Japanese pear trees are usually pruned during the winter dormant period to encourage more fruiting buds, fruiting close to main branches and reduce their heights. In many circumstances, pruning residues from orchards are disposed of by burning or landfilling. Pruning residues are considered useless and are not returned to the soil, resulting in a general loss of carbon (C) and adverse environmental impact

due to open burning. Therefore, it is necessary to find alternative ways of residue management for sustainable production.

Recently, biochar production from crop residues and its application to soil has been proposed as a novel approach to sequester carbon and reduce greenhouse gas emissions from soil (Lehmann et al. 2006). Studies reported that biochar amendment significantly reduced soil N₂O emission (Cayuela et al. 2013, Oo et al. 2018a,b). Yanai et al. (2007) and Van Zwieten et al. (2009) discussed

<https://doi.org/10.17221/114/2018-PSE>

Table 1. Physio-chemical properties of soil

Soil layer (cm)	Total N	Total C	Sand	Silt	Clay	Bulk density (g/cm ³)	NH ₄ ⁺ -N	NO ₃ ⁻ -N	pH _{KCl}	EC (mS/cm)	Available			
											Ca	Mg	K	P
0–20	0.54	6.15	26.7	50.4	22.9	0.76	27.3	18.8	6.2	0.18	4925.4	681.7	518.7	397.0
20–40	0.30	4.71	25.2	51.8	23.0	0.58	23.6	29.9	6.1	0.26	2753.4	410.4	361.8	15.4
40–60	0.14	2.93	21.4	62.6	16.0	–	21.7	78.9	6.05	0.32	1506.9	275.3	278.3	3.6

EC – electrical conductivity

that biochar application to soil could affect N₂O emissions by inducing catalytic reduction of N₂O to N₂ following oxidation and subsequent reactions of biochar with soil minerals, altering soil properties and the availability and distribution of key electron acceptors and donors, and influencing microbial community structures and microbial enzymes and processes (nitrogen (N) mineralization-immobilization turnover, nitrification, denitrification) involved in N cycling in soil. However, Saarnio et al. (2013) and Hüppi et al. (2015) observed no difference or even an increase in soil N₂O emissions after biochar application. These studies mainly focused on soil N₂O emissions after biochar incorporation into the soil under field or laboratory conditions. There is still a lack of information on the effect of surface application of biochar on N₂O emissions from no-tilled soil.

No tillage or zero tillage system is widely adopted and popular in orchard farms and all manure and fertilizers are applied on the soil surface. Under conservation agriculture, conversion of prun-

ing residue to biochar and its return to orchard soil as surface application would alter soil N₂O emission from orchard farms. Therefore, field experiment was conducted to study the effect of surface application of pruning waste biochar on N₂O emission from Japanese pear orchard soil. To our knowledge, this is the first report describing the effect of surface application of biochar to no-tilled soil on N₂O emission, and therefore it mainly focuses on emission fluxes related with soil environmental factors in this study.

MATERIAL AND METHODS

The field experiment was carried out from March to October 2017 (spring to autumn) at the Horticultural Research Institute, Ibaraki Prefecture Agricultural Research Center, Ibaraki, Japan (36°16'N, 140°26'E). The age of the Japanese pear tree was 25 years old and plant density was 380 plants/ha. The soil was classified as Andosol

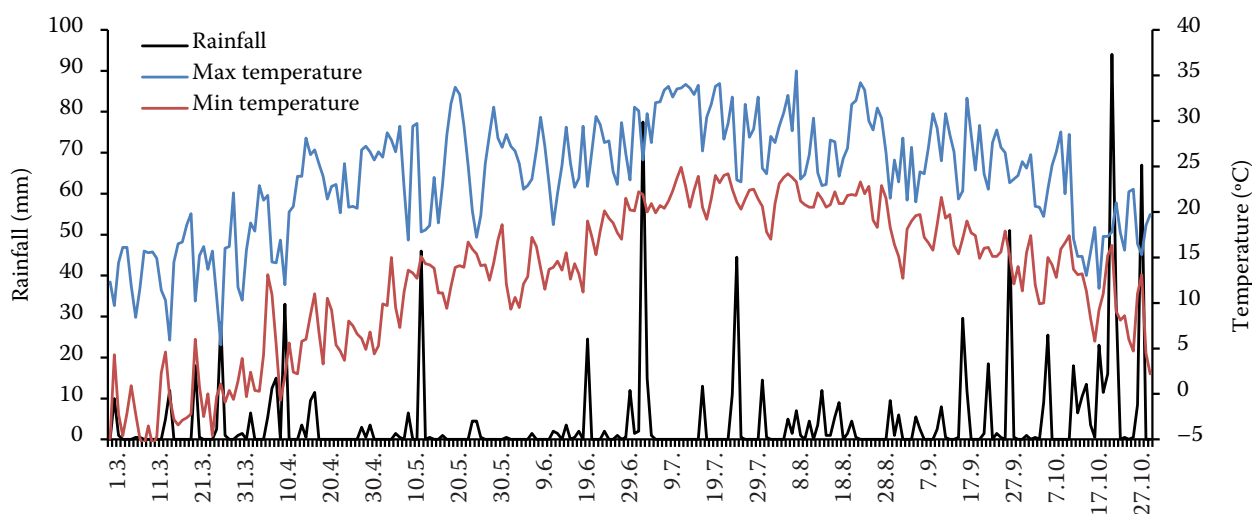


Figure 1. Daily rainfall, maximum and minimum temperatures from March to October 2017

Table 2. Properties of pruning residue biochar

Biochar [#]	Pyrolysis temperature (°C)	Total N (g/kg)	Total C (g/kg)	pH _{H₂O}	C/N ratio	Surface area (m ² /g)	Ash (%)	Volatile matter (%)	Stable C (%)	Bulk density (g/cm ³)
		500–600	5.7	374	10.3	65.6	83.9	9.8	9.7	80.5

[#](Oo et al. 2018b)

and properties are shown in Table 1. Mineral N of soil was extracted by 10% of KCl, and the content was determined by the Kjeldahl method. The content of soil available phosphorus (P) extracted by the Truog extraction method was determined by the vanadomolybdenum method (Shimadzu UV-1800, Kyoto, Japan). The available Ca, Mg and K were extracted by 1 mol/L ammonium acetate as exchangeable nutrients, and the contents were determined by using the atomic absorption spectroscopy method (Shimadzu, AA-6300, Kyoto, Japan). The rainfall and minimum and maximum temperatures during the experimental period are shown in Figure 1. Biochar was produced from carbonization of orchard pruning residues under open fire using the open burn kiln (Oo et al. 2018a). Biochar characteristics are shown in Table 2.

The experiment was laid out with a completely randomized design with three replications. The size of individual experimental plot was 25 m². Each root area was isolated by 90 cm depth of board. The treatments were: (1) control (unfertilized); (2) manure 300 kg N/ha and N fertilizer 200 kg N/ha with no biochar amendment (F + BC0); (3) the same amount of manure and N fertilizer with 2 t/ha biochar (F + BC2) and (4) with 10 t/ha biochar (F + BC10). Ammonium sulfate was used as a nitrogen source. Manure used in this study was pig manure composted with rice husk. Manure was applied on fresh weight basis with the rate of 18.6 t/ha based on N content. Properties of manure used in this experiment are shown in Table 3. The manure sample for the total contents analysis was digested by nitric acid and dissolved to water. The

total content of each nutrient was determined as described in soil analysis.

All manure and 50% of N (100 kg/ha) were applied as basal under the tree canopy on 8 March 2017. The remaining N fertilizer was applied as three splits; 30 kg N/ha was applied on 18 May and 15 June as the first and second dressings, while the remaining 40 kg N/ha was applied on 11 September as the last dressing for year 2017. The type, rate and split application of fertilizer, and individual application date were followed by the standard cultivation method in the Ibaraki prefecture, Japan. All biochar was manually broadcasted on the soil surface on 8 March 2017 as basal application and no more biochar was subsequently added (Figure 2). The size of biochar was about 3 cm in length and 0.5 cm in diameter.

Air samples used to determine soil N₂O fluxes were collected using the closed chamber method (Toma et al. 2017). Vinyl chloride chamber bases were installed throughout the experimental period under the tree canopy for each plot. At the time of sampling, lids were placed on the bases, and gas samples were collected at 0, 7 and 14 min from the time the chambers were deployed. The concentrations of N₂O were analysed with a gas chromatograph (GC 2014, Shimadzu Corporation, Kyoto, Japan) equipped with an electron capture detector (ECD). N₂O fluxes were calculated from the slope in N₂O concentration vs. time regression when their linear correlation coefficient was significant at 0.05 level. Cumulative emissions of soil N₂O were calculated in the period after basal fertilization (phase 1 – spring season: from 8 March

Table 3. Properties of manure (fresh matter basis)

pH _{H₂O}	EC (dS/m)	Moisture content (%)	NH ₄ ⁺ -N (mg/kg)	NO ₃ ⁻ -N (mg/kg)	Available (%)				Total N	Total C	
					P	K	Ca	Mg			
Manure	7.18	7.65	35.2	690.3	248.7	0.7	0.7	2.1	0.5	1.61	21.8

EC – electrical conductivity

<https://doi.org/10.17221/114/2018-PSE>



Figure 2. Application of biochar (10 t/ha) on the surface of Japanese pear orchard soil on March 2017

to 17 May); first side-dressing (phase 2 – transition from spring to summer: from 18 May to 14 June); second side-dressing (phase 3 – summer season including early autumn: from 15 June to 10 September); third side-dressing (phase 4 – autumn season: from 11 September to 18 October).

Soil temperature was continuously recorded hourly at a depth of 10 cm by using a data logger (Thermo recorder, TR-52i; T&D, Nagano, Japan). Volumetric water content of the soil at a depth of 10 cm was measured continuously (data recorded hourly) by using the sensor (Decagon 10HS, Pullman, USA) and data logger (Decagon Em5b, Pullman, USA). Water filled pore space (WFPS) of the soils was calculated from the measured VWC by the equation:

$$\text{WFPS (\%)} = (\text{VWC/porosity}) \times 100.$$

The results were statistically analysed with ANOVA using the CropStat 7.2 statistical software program (IRRI, Los Baños, Philippines).

RESULTS

Seasonal variation in soil environmental factors. Soil temperature was the lowest (3.2–3.5°C) at the beginning of experiment (early period of the spring season) and then increased gradually during the spring and summer seasons (Figure 3). High soil temperature was observed during the summer period with the highest peak of 22.4–24.6°C in July and August. Then, soil temperature showed a decreasing trend during the autumn period.

During the early period of experiment (phase 1), soil WFPS varied from 69% to 75.8% (Figure 4). Due to the data logger problem, no data was recorded during the later period of phase 1 and the whole phase 2 (spring season between 14 April and 6 June). At the beginning of the phase 3, the lowest soil WFPS was observed ranging from 64.1% to 64.4%. Then, soil WFPS showed an increasing trend (above 70%) during the summer and autumn periods.

N₂O emission and its relationship with soil environmental factors. Relatively small N₂O fluxes were observed under the unfertilized control during the phases 1, 2 and 3 (Figure 5). However, high emission peak was observed in the control during the phase 4. Soil N₂O fluxes increased soon after the basal application of fertilizers with or without biochar during the phase 1 (Figure 5). Among the treatments, the maximum values of N₂O flux were observed in the F + BC0 and F + BC2 (115.3 and 119.8 µg N/m²/h, respectively), while emission peak of F + BC10 was only 82.2 µg N/m²/h. During the phase 2 after the first N dressing, relatively low NO₂ emission fluxes were observed compared to emission fluxes from phase 1. The peak emission values ranged from 16.2 to 24.1 µg N/m²/h. In the phase 3, high emission peaks

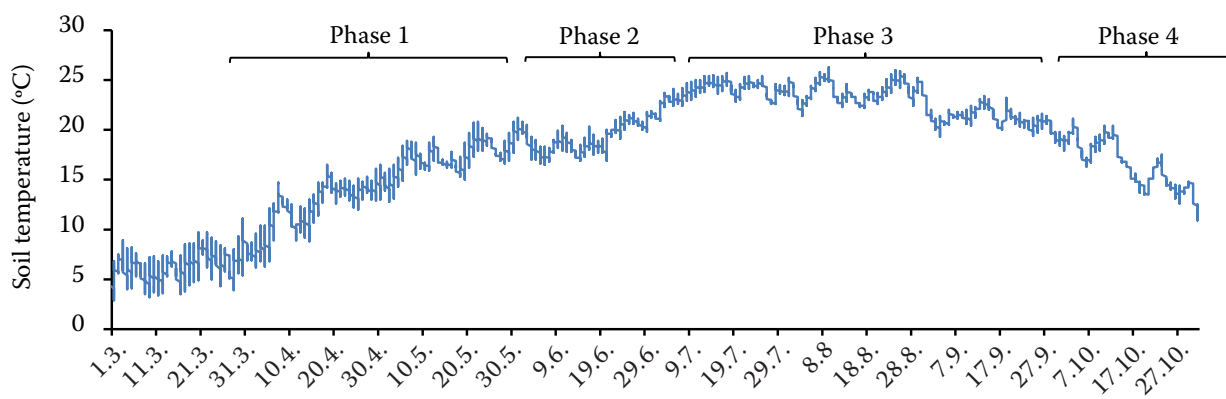


Figure 3. Seasonal variation in soil temperature during the experimental period from March to October 2017

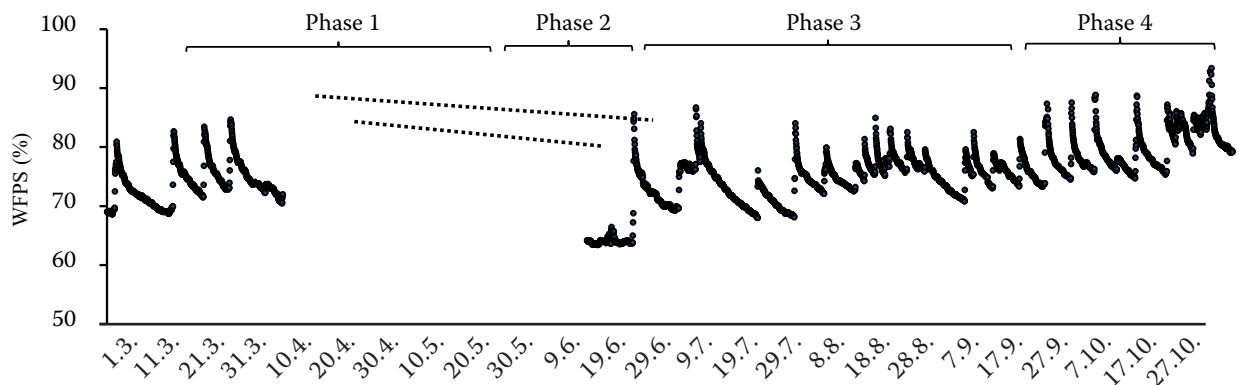


Figure 4. Seasonal variation in soil water filled pore space (WFPS) during experimental period from March to October 2017. No data was recorded between 14 April to 6 June

were observed soon after the second N dressing. The maximum values of N_2O flux were observed in the F + BC0 and F + BC10 (254.6 and 222.8 $\mu g N/m^2/h$, respectively), while emission peak of F + BC2 was only 96.6 $\mu g N/m^2/h$. During the phase 4 after the third N dressing, high emission peaks were also observed in all the treatments and then decreased toward the end of the experimental period. The peak emission values of F + BC10, F + BC2, and F + BC0 were 218.7, 169.6, and 172.6 $\mu g N/m^2/h$, respectively.

The lowest soil cumulative N_2O emission (0.46 kg N/ha) was observed in the unfertilized control compared to the other treatments (Table 4). Under the control conditions, the highest contribution in cumulative N_2O emission was observed in the

phase 3 (31% of the total emission in summer) and phase 4 (64% of the total emission in autumn), while phase 1 and phase 2 accounted for only 3% and 2% of the total emission, respectively. Because of the application of manure and N fertilizer, cumulative emissions in F + BC0, F + BC2 and F + BC10 were significantly higher compared to the control. Under the treatment applications, contributions in cumulative N_2O emissions from phases 1, 2, 3 and 4 were ranged from 17–26, 2–3, 35–43, and 34–37% of the total emission, respectively. Phase 3 (summer) and phase 4 (autumn) showed the highest range of soil N_2O emissions compared to the other periods. Soil cumulative N_2O emissions showed no difference between the F + BC0 and biochar treatments (Table 4). During the phase 1, relative

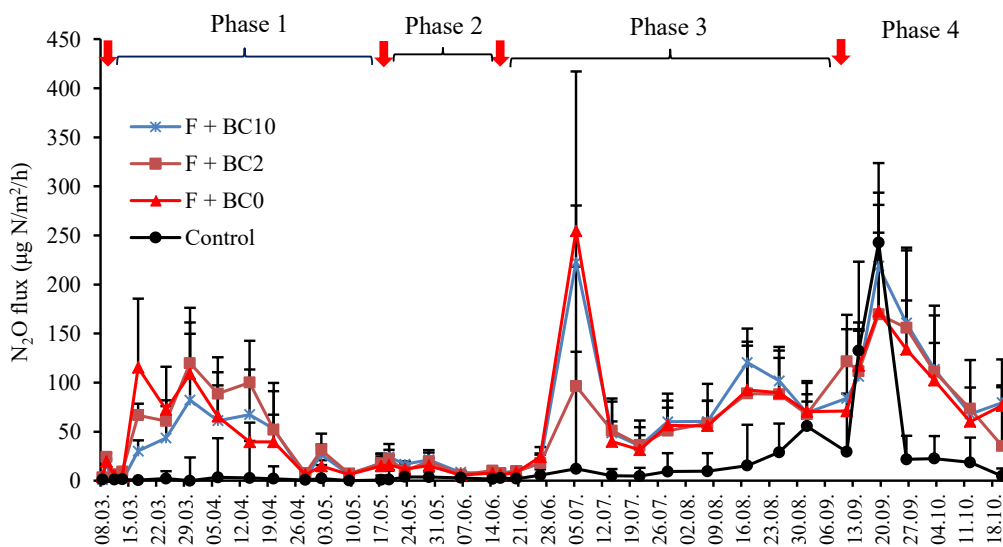


Figure 5. Seasonal variation in soil N_2O emissions from the Japanese pear orchard. Error bars indicate standard deviation ($n = 3$). Arrows indicate, first, second, third and fourth split application of fertilizer. Control – unfertilized; F + BC0 – manure 300 kg N/ha and N fertilizer 200 kg N/ha with no biochar amendment; F + BC2 – the same amount of manure and N fertilizer with 2 t/ha biochar; F + BC10 – with 10 t/ha biochar

<https://doi.org/10.17221/114/2018-PSE>

Table 4. Cumulative N₂O emission for the different periods

	Cumulative N ₂ O emission (kg N/ha)				
	phase 1 8 Mar.–17 May	phase 2 18 May–14 June	phase 3 15 June–10 Sep.	phase 4 11 Sep.–18 Oct.	total emission
Control	0.013 ± 0.004 ^b	0.010 ± 0.002 ^b	0.141 ± 0.052 ^b	0.291 ± 0.230 ^b	0.455 ± 0.342 ^b
F + BC0	0.354 ± 0.125 ^a	0.034 ± 0.012 ^a	0.729 ± 0.260 ^a	0.568 ± 0.103 ^a	1.684 ± 0.605 ^a
F + BC2	0.430 ± 0.020 ^a	0.040 ± 0.005 ^a	0.580 ± 0.115 ^a	0.625 ± 0.200 ^a	1.675 ± 0.359 ^a
F + BC10	0.304 ± 0.106 ^a	0.045 ± 0.012 ^a	0.767 ± 0.307 ^a	0.651 ± 0.258 ^a	1.766 ± 0.621 ^a
Analysis of variance					
Treatment	**	*	*	*	*
	Contribution to total emission (%)				total (%)
	phase 1	phase 2	phase 3	phase 4	
Control	3	2	31	64	100
F + BC0	21	2	43	34	100
F + BC2	26	2	35	37	100
F + BC10	17	3	43	37	100

Numbers in the table represent means ± standard deviation ($n = 3$). * $P < 0.05$, ** $P < 0.01$. Control – unfertilized; F + BC0 – manure 300 kg N/ha and N fertilizer 200 kg N/ha with no biochar amendment; F + BC2 – the same amount of manure and N fertilizer with 2 t/ha biochar; F + BC10 – with 10 t/ha biochar

low cumulative N₂O emission from the F + BC10 treatment (0.30 kg N/ha) was observed compared to F + BC0 (0.35 kg N/ha) and F + BC2 (0.43 kg N/ha). However, opposite results were observed in the treatment F + BC10 that showed relatively high N₂O emission during phase 2, 3, and 4 compared to F + BC0 and F + BC2, although it was not significant. The means of the total cumulative N₂O emissions from F + BC0, F + BC2, and F + BC10 were 1.684, 1.675, and 1.766 kg N/ha, respectively.

There was a strong positive relationship between N₂O emissions and soil environmental factors in this

study (Figure 6). High N₂O emissions were observed under high soil temperature range of 18–25°C. N₂O emissions also increased with increasing water filled pore space and peak emissions occurred at high soil moisture ranging from 75% to 80% WFPS.

DISCUSSION

Under the unfertilized control, high N₂O fluxes during the later period of phase 3 and early emission peak of phase 4 suggested that the decompo-

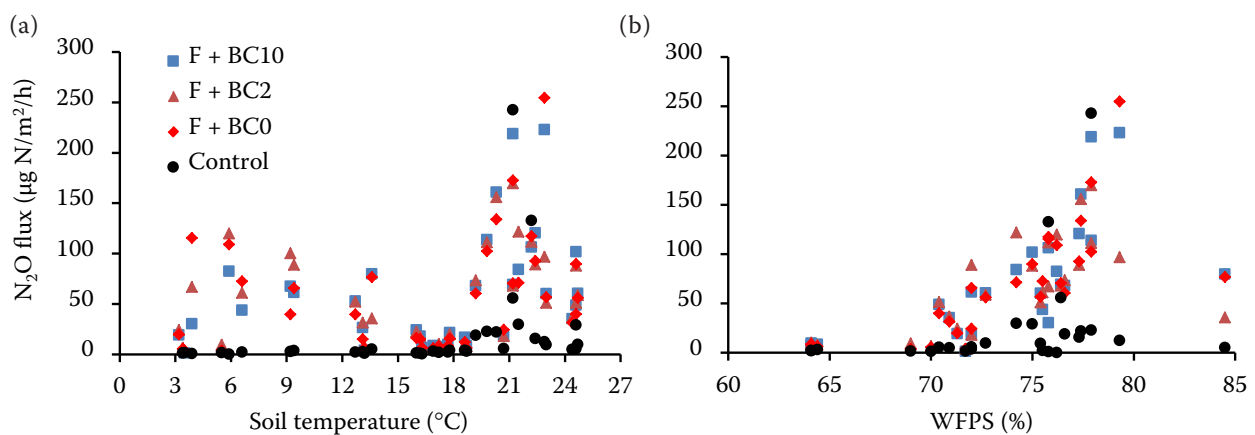


Figure 6. Relationship between N₂O emission and (a) soil temperature and (b) soil water filled pore space (WFPS) during the experimental period. Control – unfertilized; F + BC0 – manure 300 kg N/ha and N fertilizer 200 kg N/ha with no biochar amendment; F + BC2 – the same amount of manure and N fertilizer with 2 t/ha biochar; F + BC10 – with 10 t/ha biochar

sition of native organic materials under high soil temperature during summer contributed to the production of N_2O (Figures 3 and 5). High emission peak during phase 4 was associated with high precipitation (215 mm in rainfall during phase 4) and related to high soil moisture content of 77.9% WFPS (Figures 1 and 4). This result was supported by strong relationship between N_2O emission and soil moisture content (Figure 6). Perdomo et al. (2009) also reported the largest N_2O flux after rain or during periods of high soil temperature.

An increase in N_2O fluxes during the phase 1 after the basal application indicated that added manure and nitrifiable N were the main source for N_2O production and nitrification might be the main process producing N_2O in soil under the low soil temperature (Figures 3 and 5). Öquist et al. (2007) noted that a substantial fraction of N_2O produced in cold soils is derived from nitrification. The N_2O production during nitrification increased when the soil organic matter content increased and with an increase in soil moisture and in soil temperature (5–40°C), by addition of nitrifiable N forms, animal manures and plant residues (Bremner 1997). However, because of the high soil WFPS that ranged from 69–75.8% during the phase 1 due to high precipitation (230 mm in rainfall during phase 1), denitrification process might also have contributed for high N_2O fluxes. Low N_2O fluxes during the phase 2 after the first N dressing might be the result of low soil moisture content under low precipitation (16 mm in rainfall during phase 2) (Figures 4 and 5). Ball et al. (2002) discussed that application of N fertilizers by itself did not always enhance N_2O emission and that weather conditions at the time of fertilizer application influenced N_2O emissions. Although, there was no soil moisture data recorded during that period, relatively low rainfall during the phase 2 proved low soil moisture in that period. Low soil moisture decreases microbial activity by reducing diffusion of soluble substrates, microbial mobility and intracellular water potential (Schjønning et al. 2003) and therefore reduces soil N_2O fluxes. The increase in soil N_2O fluxes during the phase 3 and phase 4 was associated with high soil temperature and moisture content due to high sum of temperatures and precipitation (2134°C and 740°C in temperature and 309 mm and 215 mm in rainfall during phase 3 and 4, respectively) (Figures 3–5). In both phases, soil water content

ranged from 70.9% to 84.5% WFPS, which indicated that denitrification appeared to be the main process producing N_2O in soil. This result was further supported by regression analysis, which revealed that N_2O emission was positive related to soil moisture content and high emission was observed under high soil moisture content of 75% to 80% WFPS (Figure 6). Khalid et al. (2007) observed that soil N_2O emissions had their optimum in the range of 70–80% WFPS depending on soil type.

Cumulative N_2O emission from the unfertilized control (0.46 kg N/ha) was comparably higher than the reported cumulative N_2O emissions from well-drained agricultural fields in Japan (0.36 kg N/ha) (Akiyama et al. 2006). However, high soil N_2O emissions (1.7 kg N/ha) from unfertilized no-tilled citrus orchard field was observed by Toma et al. (2017). They discussed that citrus orchard fields had a higher potential for N_2O production than other agricultural fields.

Significantly high cumulative N_2O emissions from F + BC0, F + BC2, and F + BC10 over the unfertilized control were due to fertilizations (Table 4). Surface application of biochar treatments (F + BC2 and F + BC10) showed no significant effect on N_2O emissions compared to F + BC0 in this study. However, in our previous incubation study, surface application of 40 t/ha and 100 t/ha reduced N_2O emission (Oo et al. 2018b,c). Yet, no difference was detected at the low rate 20 t/ha biochar application on the soil surface (Oo et al. 2018b). No significant effect of biochar on N_2O emission from the orchard soil might be caused by the application dose used in this study.

Although some previous studies reported a significant decrease in soil N_2O emissions under biochar amendment (Cayuela et al. 2013, Oo et al. 2018a), no significant effect on soil N_2O emission in this study was in agreement with other studies (Saarnio et al. 2013, Hüppi et al. 2015). However, biochar was incorporated to soil in their studies, while in this study biochar was applied on the soil surface. Although there is limited information on the surface application of biochar on soil N_2O emission from agricultural soil, the presence of straw or residues on the soil surface significantly affects soil N_2O emission (Signor and Cerri 2013). The maintenance of residues on the soil surface affects the N mobilization and immobilization and, consequently, the N availability in the soil and also the nitrification and denitrification pro-

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cesses (Signor and Cerri 2013). In some previous incubation studies, surface application of biochar improved soil pH and increased soil total C and C:N ratio, which influenced the reduction in soil N₂O emission (Oo et al. 2018a,b). In this study, the changes of soil properties under surface application of fertilizers and biochar might also influence soil N₂O emission from the Japanese pear orchard soil under field conditions. Therefore, it is necessary not only to analyse properties of orchard soil such as pH, total C, and soil mineral N content during the experimental period, but also to collect yield data to determine the influencing parameters on N₂O emission from orchard soil. In this study, soil N₂O emissions were not influenced by surface application of biochar because of the low application rates and further research is thus necessary for mitigation of N₂O emission from no-tilled orchard soil with high rates of biochar. Our results indicated that biochar pyrolyzed from the pruning waste residues of orchard can be returned to orchard soil as surface application without affecting soil N₂O emissions.

Acknowledgements

We would like to thank the editor and reviewers for their time spent on reviewing our manuscript and their comments helping us improve the article.

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Received on February 22, 2018

Accepted on August 23, 2018

Published online on November 9, 2018