doi: 10.17221/618/2016-PSE

# Effects of biochar addition on $CO_2$ and $CH_4$ emissions from a cultivated sandy loam soil during freeze-thaw cycles

Xiang LIU[1,2,3], Zhiming QI[1], Quan WANG[3], Zhiwen MA[1,2], Lanhai LI[1,*]

[1]*State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, Xinjiang, P.R. China*
[2]*University of Chinese Academy of Sciences, Beijing, P.R. China*
[3]*Faculty of Agriculture, Shizuoka University, Shizuoka, Japan*
**Corresponding author: lilh@ms.xjb.ac.cn*

**ABSTRACT**

Liu X., Qi Z.M., Wang Q., Ma Z.W., Li L.H. (2017): Effects of biochar addition on $CO_2$ and $CH_4$ emissions from a cultivated sandy loam soil during freeze-thaw cycles. Plant Soil Environ., 63: 243–249.

This study was conducted to examine the effects of biochar additions (0, 2 and 4%, w/w) on soil carbon dioxide ($CO_2$) and methane ($CH_4$) emissions during freeze-thaw cycles (FTC). The results showed that soil $CO_2$ emissions were stimulated by both FTC and biochar addition. However, the differences in soil $CO_2$ emissions between control (CK) and FTC treatments were not significant when biochar addition rate was 4%, indicating that high biochar addition rate may have stronger effect on stimulating soil $CO_2$ emissions than FTC. The increased soil dissolved organic carbon content, which attributed to the labile carbon in biochar, was the likely reason for the increased $CO_2$ emissions. The negative $CH_4$ emissions were promoted by biochar, especially under FTC conditions; possibly due to the structure of biochar soil aeration increased, which formed a favourable environment for methanotrophs. The results of this study indicate that biochar additions can increase soil $CO_2$ emissions and $CH_4$ uptakes during FTC, and such effects are different from those under CK conditions.

**Keywords**: agricultural soil; greenhouse gas mitigation; soil labile organic carbon; soil amendment; non-vegetation period

Carbon dioxide ($CO_2$) and methane ($CH_4$) are two major greenhouse gases (GHGs), which play important roles in the biogeochemical carbon (C) cycle as well as global warming (IPCC 2007). Agricultural soils are identified as major sources of GHGs (Smith et al. 2008). It is estimated that over 50 Gt of $CO_2$ were emitted from agricultural soils to the atmosphere through the mineralization of soil organic C (SOC) at the end of the 20$^{th}$ century (Paustian et al. 2000). Agriculture also accounts for 52% of global anthropogenic $CH_4$ emission (Smith et al. 2008). In the context of global change, effective measures are strongly needed to mitigate $CO_2$ and $CH_4$ emissions from agricultural soils.

Biochar, which is a C-rich product derived from the slow pyrolysis of organic materials under oxygen ($O_2$) limited conditions, has drawn increasing attention for its potential to be used as an amendment to mitigate soil GHGs emissions (Liu et al. 2014). However, the observation periods of previous studies were mainly focused on vegetation periods (Castaldi et al. 2011, Zhang et al. 2012). In recent decades, enhanced soil GHGs emissions during

Supported by the Provincial Department of Science and Technology, the Xinjiang Uygur Autonomous Region, Project No. 2014KL015. The first author appreciates the financial support from the China Scholarship Council for his joint Ph.D. Scholarship, Project No. 201504910637.

doi: 10.17221/618/2016-PSE

freeze-thaw period were reported in both field and incubation investigations (Wolf et al. 2010, Wang et al. 2014, Wu et al. 2014). Some studies further demonstrated that freeze-thaw induced GHGs emissions were important parts of the annual GHGs budget (Liang et al. 2007, Wolf et al. 2010). In a short-term laboratory study, Kettunen and Saarnio (2013) found that soils amended with biochar decreased soil $N_2O$ emissions by 61% during freeze-thaw cycles (FTC). However, to the best of our knowledge, there have been no studies on responses of soil $CO_2$ and $CH_4$ emissions to biochar addition during FTC.

Soil $CO_2$ and $CH_4$ are believed to be produced mostly from microbial processes, such as methanogenesis and biological oxidation of SOC (Smith et al. 2008). Previous studies demonstrated that soil microbial activities could be considerably influenced by FTC due to the important role of temperature on microbial metabolism. FTC can disrupt soil aggregates and some microbial cells, induce the release of aggregate-protected organic C and the decomposition of microbial cells (Yergeau and Kowalchuk 2008, Kim et al. 2012). These accumulated substrates can be utilized by microorganisms and then enhance microbial metabolism during thawing period (Kim et al. 2012). Soil dissolved organic C (DOC) and microbial biomass C (MBC) are easily accessible C sources for soil microorganisms (Wang et al. 2014, Yeboah et al. 2016). Previous studies proved that soil DOC and MBC contents were closely related to soil C emissions (Wang et al. 2014, Shaaban et al. 2016). However, under the joint effects of biochar and FTC, the relationships between soil C emissions and DOC/MBC contents are still poorly understood.

In this study, FTC was simulated in laboratory to: (1) examine the effects of biochar addition on soil $CO_2$ and $CH_4$ emissions, DOC and MBC contents during FTC; (2) estimate the relationships among soil C emissions, DOC and MBC contents under the joint effects of FTC and biochar.

## MATERIAL AND METHODS

**Soil sampling and biochar preparation**. Soil samples were collected in a depth of 20 cm from a maize (*Zea mays* L.) field in the Ili River Valley (43°27'N, 82°54'E), northwest China. The soil is classified as Haplic Kastanozems (FAO) with a sandy loam texture (4.2% clay, 23.2% silt and 72.6% sand). Soil samples were air-dried in the shade and sieved (≤ 2 mm) with removal of any visible plant material. Sieved soil samples were homogenized and then stored at 4°C until the incubation experiment.

Biochar used for this experiment was produced using bamboo subjected to pyrolysis at 500–600°C by the Seek Bio-Technology Company in Shanghai, China. The biochar was then ground up, passed through a 2 mm sieve and mixed thoroughly before experimental use.

**Experimental design**. A series of 250 mL Erlenmeyer flasks were prepared with 60.0 g (oven-dry basis) of soil samples. Biochar was then mixed well with soils at addition rates of 0% (BC0); 2% (BC2) and 4% (BC4) (w/w). Deionized water was added to the mixtures to maintain 60% of maximum water holding capacity (MWHC). All flasks were pre-incubated at 25°C in the dark condition for one week. After pre-incubation, flasks of each addition rate were randomly divided into three equal groups to experience three different FTC treatments: (1) treatment without FTC (CK); (2) treatment with small amplitude of FTC (SFT); (3) treatment with large amplitude of FTC (LFT). Therefore, there were nine treatments (three biochar addition rates × three FTC amplitudes) in this experiment. For SFT, a single FTC consisted of freezing at –5°C for 24 h and thawing at 5°C for 24 h. By contrast, flasks of LFT were frozen at –10°C for 24 h and then thawed at 10°C for 24 h. Fifteen FTCs (30 days) were conducted in total to simulate the freeze-thaw period under field conditions. Flasks of CK were incubated at 5°C during the entire incubation. At the end of every two FTCs, deionized water was added into each flask to maintain constant soil moisture. Three flasks of each treatment were randomly selected for gas sampling after 1$^{st}$, 3$^{rd}$, 5$^{th}$, 10$^{th}$ and 15$^{th}$ FTC. Soils of each flask were then destructively sampled for the measurements of soil DOC and MBC contents.

**Chemical analysis**. The pH and electrical conductivity (EC) of soil and biochar were measured in a volume ratio ($H_2O$) of 1:5 (w/v) using a pH meter (SevenEasy, Mettler-Toledo, Greifensee, Switzerland) and an EC meter (DDSJ-308A, Rex, Shanghai, China), respectively (Zhang et al. 2014). Soil total N ($N_{tot}$) was determined using an automatic azotometer (Kjeltec 8400, FOSS, Hillerød,

doi: 10.17221/618/2016-PSE

Denmark) according to the Kjeldahl method (Lu 1999). SOC was measured using the $H_2SO_4$-$K_2Cr_2O_7$ oxidation method (Lu 1999). The C and N contents of biochar were measured using an elemental analyser (vario Micro cube, Elementar, Hanau, Germany) (Lan et al. 2017). The ammonium N ($NH_4^+$-N) and nitrate N ($NO_3^-$-N) of soil and biochar were measured using a continuous flow analyzer (AA3, SEAL Analytical, Norderstedt, Germany) (Yao et al. 2009). Soil texture was determined using a laser diffraction particle analyzer (Mastersizer 2000, Malvern, UK) (Gui et al. 2010). DOC of fresh soils and biochar were extracted with deionized water and 2 mol/L KCl (1:10, w/v), respectively, at 250 rpm for 30 min; the extracts were filtered (0.45 μm) after centrifuging at 8000 rpm for 10 min (Jones and Willett 2006). Biochar samples were recovered for further extraction using 2 mol/L hot (95°C) KCl (1:10, w/v) at 250 rpm for 16 h before centrifuging and filtering (0.45 μm). DOC contents of extracts were determined using a TOC analyzer (model 1030, OI Analytical, College Station, USA) and biochar DOC was obtained by adding up the DOC contents of both cold and hot KCl extracts (Lan et al. 2017). Soil MBC was measured using the $CHCl_3$ fumigation-$K_2SO_4$ extraction method (1:4, w/v). The extracts were analyzed at 280 nm using an UV spectrophotometer (Cary 60, Agilent Technologies, Santa Clara, USA) (Nunan et al. 1998). Selected physicochemical properties of soil and biochar are shown in Table 1.

The concentrations of $CO_2$ and $CH_4$ were detected using a gas chromatograph (7890B, Agilent Technologies, Santa Clara, USA). The gas chromatograph was equipped with a thermal conductivity detector for $CO_2$ analysis and a flame ionization detector for $CH_4$ analysis. The $CH_4$ and $CO_2$ emissions were calculated according to the method of Lim and Choi (2014). Cumulative gas emissions during the whole incubation were directly computed from the measured emissions and were estimated by linear interpolation for days when no measurements were available (Gao et al. 2013).

**Statistical analysis**. The effects of FTC amplitude and biochar addition rate on soil C emissions, DOC and MBC contents were tested using two-way ANOVA. Differences in cumulative gas emissions of the entire incubation among different FTC amplitudes or biochar addition rates were examined using one-way ANOVA with *LSD* (least significant difference) test. Data sets were tested for normality and heterogeneity before analyses. Pearson correlation test was employed to examine the relationships among soil C emissions, DOC and MBC contents. Differences and correlations were considered statistically significant if $P < 0.05$ and highly significant if $P < 0.001$. SPSS 16.0 (SPSS Inc., Chicago, USA) were used to perform statistical analysis.

## RESULTS AND DISCUSSION

**Effects of biochar addition on soil DOC and MBC contents during FTC**. In general, soil DOC contents of BC2 and BC4 were significantly higher than those of BC0 for all temperature treatments (Figure 1, Table 2), indicating that soil DOC content can be increased by adding biochar. Lin et al. (2012) demonstrated that labile or leachable organic C could be generated during the production of biochar. These C can be adsorbed onto the surface of biochar and act as a source of soil DOC after being mixed into soils (Lin et al. 2012). In the present study, the high DOC content of biochar (695.1 mg/kg, Table 1) demonstrated that the DOC in biochar was the main reason for the increased soil DOC contents after adding biochar. Except for BC2 under CK condition, DOC contents of other treatments decreased by 8.4–43.3% after the whole incubation. Soil DOC utilized by soil

Table 1. Selected physicochemical properties of soil and biochar (mean ± standard error, $n = 3$)

| | $C_{org}$ | $C_{tot}$ | $N_{tot}$ | DOC | $NH_4^+$-N | $NO_3^-$-N | pH | EC | MWHC |
|---|---|---|---|---|---|---|---|---|---|
| | (g/kg) | | | (mg/kg) | | | | (μs/cm) | (%) |
| Soil | 11.0 ± 0.2 | – | 1.2 ± 0.1 | 285.6 ± 2.1 | 4.0 ± 0.10 | 21.5 ± 0.1 | 8.0 ± 0.04 | 315.3 ± 2.1 | 39.5 |
| Biochar | – | 664.8 ± 37.1 | 9.8 ± 0.5 | 695.1 ± 62.3 | 3.1 ± 0.2 | 1.8 ± 0.0 | 9.2 ± 0.1 | 2393.3 ± 57.7 | – |

– not detected. $C_{org}$ – organic carbon; $C_{tot}$ – total carbon; $N_{tot}$ – total nitrogen; DOC – dissolved organic carbon; EC – electrical conductivity; MWHC – maximum water holding capacity

doi: 10.17221/618/2016-PSE

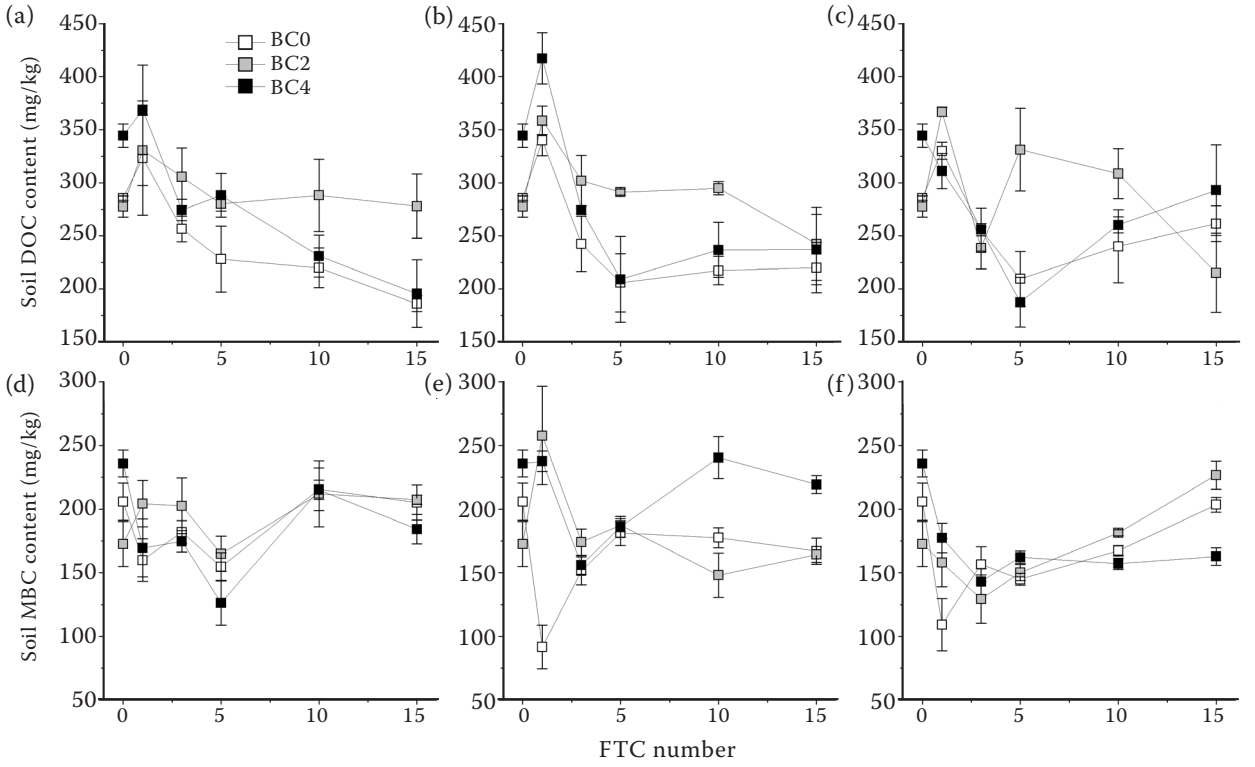


Figure 1. Responses of soil disolved organic carbon (DOC) – (a) treatment without freeze-thaw cycles (FTC) (CK); (b) treatment with small amplitude of FTC (SFT); (c) treatment with large amplitude of FTC (LFT), and microbial biomass carbon (MBC) – (d) CK; (e) SFT; (f) LFT contents to biochar additions during the incubation. BC0 – 0%; BC2 – 2%; BC4 – 4% (w/w). Bars represent the standard error of the mean ($n$ = 3)

microorganisms was the likely reason for such decreases because soil DOC is an easily accessible C source for soil microorganisms (Wang et al. 2014). However, the effect of FTC amplitude on soil DOC was not significant (Table 2), suggesting that the C in biochar may be quite stable and able to endure the FTC conditions.

As shown in Figure 1e,f, soil MBC contents of BC0 showed sharp decreases after the 1st FTC, and then gradually increased during the rest of FTCs. The results were in agreement with observations of Wang et al. (2014). The sharp decreases might be attributed to some microbial cells that were damaged or destroyed by sudden changes in temperature (Yergeau and Kowalchuk 2008). Thereafter, soil microorganisms might be adapted to this environmental change. Under FTC conditions, MBC contents of soils with different biochar addition rates generally decreased in the following order: BC4 > BC2 > BC0. The results indicated that biochars were helpful in increasing soil microbial biomass during FTC. The reason was possibly that the macropores (> 200 nm) of biochars could serve as habitats for soil microorganisms such as bacteria, fungi, and protozoa (Gul et al. 2015), and protected them from being disturbed by the FTC process. The high EC of biochar might also influence soil microbial biomass because salinity is identified as an important factor that affects the growth of soil microorganisms (Wong et al. 2008), which should be paid more attention to in the future.

Table 2. Results of two-way ANOVA ($P$-values) testing the effects of freeze-thaw cycles (FTC) amplitude and biochar addition rate on soil $CO_2$ emission, $CH_4$ emission, disolved organic carbon (DOC) content and microbial biomass carbon (MBC) content

| Source | DOC | MBC | $CO_2$ | $CH_4$ |
|---|---|---|---|---|
| FTC amplitude | 0.691 | **< 0.001** | **< 0.05** | **< 0.001** |
| Biochar addition rate | **< 0.05** | 0.352 | **< 0.001** | **< 0.05** |
| FTC amplitude × biochar addition rate | 0.936 | **< 0.05** | **< 0.05** | **< 0.001** |

Boldface values indicate which effects were significant

**Effects of biochar addition on soil $CO_2$ and $CH_4$ emissions during FTC**. Similar to soil DOC,

doi: 10.17221/618/2016-PSE

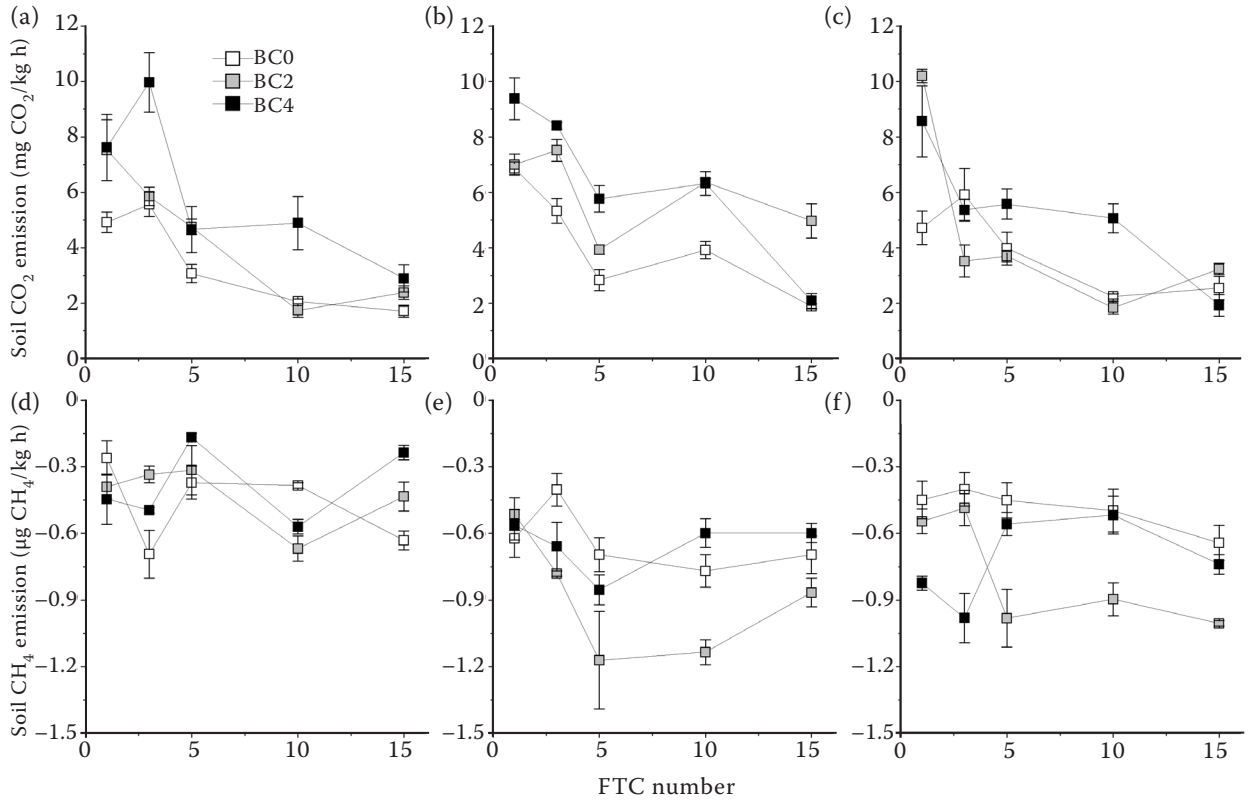


Figure 2. Responses of soil $CO_2$ – (a) treatment without freeze-thaw cycles (FTC) (CK); (b) treatment with small amplitude of FTC (SFT); (c) treatment with small amplitude of FTC (LFT), and $CH_4$ – (d) CK; (e) SFT; (f) LFT emissions to biochar additions during the incubation. BC0 – 0%; BC2 – 2%; BC4 – 4% (w/w). Bars represent the standard error of the mean ($n$ = 3)

soil $CO_2$ emissions of most treatments gradually decreased with the increase of incubation time (Figure 2a–c). For BC0, cumulative $CO_2$ emissions from soils treated with FTC were significantly higher than those from soils under CK condition (Table 3), implying that soil $CO_2$ emissions can be increased by FTC. This was possibly due to some FTC-destroyed soil aggregates and microbial cells through the transition phase of soil water and low temperature, which increased the availability of substrate and microbial respiration (Kim et al. 2012). Biochar additions increased cumulative $CO_2$ emissions by 6.8–50.9% (BC2) and 41.8–79.9% (BC4) compared to BC0 (Table 3), demonstrating that biochar additions may stimulate soil $CO_2$ emissions. This finding was in agreement with

Table 3. Cumulative $CO_2$ and $CH_4$ emissions of each treatment during the whole incubation (mean ± standard error)

| Treatment | Cumulative $CO_2$ emission (g C/kg) | | | Cumulative $CH_4$ emission (mg C/kg) | | |
|---|---|---|---|---|---|---|
| | CK | SFT | LFT | CK | SFT | LFT |
| BC0 | $2.19 \pm 0.02^{Cb}$ | $2.75 \pm 0.12^{Ab}$ | $2.51 \pm 0.02^{Bb}$ | $0.27 \pm 0.01^{Ca}$ | $0.48 \pm 0.01^{Ab}$ | $0.37 \pm 0.03^{Bc}$ |
| BC2 | $2.72 \pm 0.06^{Bb}$ | $4.15 \pm 0.09^{Aa}$ | $2.68 \pm 0.06^{Bb}$ | $0.34 \pm 0.02^{Ca}$ | $0.70 \pm 0.02^{Aa}$ | $0.61 \pm 0.02^{Ba}$ |
| BC4 | $3.94 \pm 0.35^{Aa}$ | $3.90 \pm 0.14^{Aa}$ | $3.64 \pm 0.28^{Aa}$ | $0.36 \pm 0.04^{Ba}$ | $0.48 \pm 0.03^{Ab}$ | $0.47 \pm 0.01^{Ab}$ |

Uppercase letters indicate significant differences ($P < 0.05$) among freeze-thaw cycles (FTC) amplitudes while under the same biochar addition rate; lowercase letters indicate significant differences ($P < 0.05$) among biochar addition rates while under the same FTC amplitude. CK – treatment without FTC; SFT – treatment with small amplitude of FTC; LFT – treatment with small amplitude of FTC; BC0 – 0%; BC2 – 2%; BC4 – 4% (w/w)

doi: 10.17221/618/2016-PSE

Table 4. Correlation coefficients ($R$) among soil $CO_2$ emission, $CH_4$ emission, disolved organic carbon (DOC) content and microbial biomass carbon (MBC) content ($n$ = 135)

| | DOC | MBC | $CO_2$ | $CH_4$ |
|---|---|---|---|---|
| DOC | 1 | | | |
| MBC | –0.027 | 1 | | |
| $CO_2$ | **0.436**** | –0.033 | 1 | |
| $CH_4$ | 0.066 | **0.194*** | –0.008 | 1 |

Boldface values indicate correlations which are significant
*$P$ < 0.05; **$P$ < 0.01

Zhang et al. (2012), who attributed such increases to enhanced soil labile C contents by adding biochar. In this study, BC2 and BC4 generally showed higher DOC contents than BC0. The results of Pearson correlation analysis showed that soil $CO_2$ emission was significantly correlated to soil DOC content (Table 4), partly supporting the previous assertions. However, cumulative $CO_2$ emissions of different temperature treatments did not differ significantly at BC4 (Table 4). This indicated that high biochar addition rate might have a stronger effect on stimulating soil $CO_2$ emissions than FTC, which might weaken the differences in soil $CO_2$ emission between CK and FTC.

Soil $CH_4$ emissions were negative for all treatments (Figure 2d–f), varying from –0.17 to –1.17 μg $CH_4$/(kg h) during the whole incubation period. Soil $CH_4$ uptakes were promoted by biochar, especially under FTC conditions (Table 3). Karhu et al. (2011) indicated that pores of biochar could increase aeration, porosity and surface area of soils, thus forming favourable environment for methanotrophs. Furthermore, low temperatures can reduce activities of some aerobic microorganisms, resulting in more $O_2$ in soils. The increased $O_2$ may favour methane oxidation while inhibits methanogenesis (Ding and Cai 2007). The positive correlation between soil MBC content and $CH_4$ uptake indicated that soil microorganism was an important factor that affected $CH_4$ emission (Table 4).

Although there are some limitations in this study (a short incubation period with single soil and biochar under laboratory conditions without plants), the results still indicate that the effects of biochar additions on soil C emissions may be different between CK and FTC conditions. The effects of more types of biochar on GHGs emissions from different kinds of soil during FTC will be focused in further studies.

## REFERENCES

Castaldi S., Riondino M., Baronti S., Esposito F.R., Marzaioli R., Rutigliano F.A., Vaccari F.P., Miglietta F. (2011): Impact of biochar application to a Mediterranean wheat crop on soil microbial activity and greenhouse gas fluxes. Chemosphere, 85: 1464–1471.

Ding W.-X., Cai Z.-C. (2007): Methane emission from natural wetlands in China: Summary of years 1995–2004 studies. Pedosphere, 17: 475–486.

Gao X.P., Tenuta M., Nelson A., Sparling B., Tomasiewicz D., Mohr R.M., Bizimungu B. (2013): Effect of nitrogen fertilizer rate on nitrous oxide emission from irrigated potato on a clay loam soil in Manitoba, Canada. Canadian Journal of Soil Science, 93: 1–11.

Gui D.W., Lei J.Q., Zeng F.J., Runge M., Mu G.J., Yang F.X., Zhu J.T. (2010): Ordination as a tool to characterize soil particle size distribution, applied to an elevation gradient at the north slope of the Middle Kunlun Mountains. Geoderma, 158: 352–358.

Gul S., Whalen J.K., Thomas B.W., Sachdeva V., Deng H.Y. (2015): Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. Agriculture, Ecosystems and Environment, 206: 46–59.

IPCC (2007): Changes in Atmospheric Constituents and in Radiative Forcing. Cambridge, Cambridge University Press.

Jones D.L., Willett V.B. (2006): Experimental evaluation of methods to quantify dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) in soil. Soil Biology and Biochemistry, 38: 991–999.

Karhu K., Mattila T., Bergström I., Regina K. (2011): Biochar addition to agricultural soil increased $CH_4$ uptake and water holding capacity – Results from a short-term pilot field study. Agriculture, Ecosystems and Environment, 140: 309–313.

Kettunen R., Saarnio S. (2013): Biochar can restrict $N_2O$ emissions and the risk of nitrogen leaching from an agricultural soil during the freeze-thaw period. Agricultural and Food Science, 22: 373–379.

Kim D.-G., Vargas R., Bond-Lamberty B., Turetsky M.R. (2012): Effects of soil rewetting and thawing on soil gas fluxes: A review of current literature and suggestions for future research. Biogeosciences, 9: 2459–2483.

Lan Z.M., Chen C.R., Rashti M.R., Yang H., Zhang D.K. (2017): Stoichiometric ratio of dissolved organic carbon to nitrate regulates nitrous oxide emission from the biochar-amended soils. Science of the Total Environment, 576: 559–571.

doi: 10.17221/618/2016-PSE

Liang W., Shi Y., Zhang H., Yue J., Huang G.-H. (2007): Greenhouse gas emissions from northeast China rice fields in fallow season. Pedosphere, 17: 630–638.

Lim S.-S., Choi W.-J. (2014): Changes in microbial biomass, $CH_4$ and $CO_2$ emissions, and soil carbon content by fly ash co-applied with organic inputs with contrasting substrate quality under changing water regimes. Soil Biology and Biochemistry, 68: 494–502.

Lin Y., Munroe P., Joseph S., Henderson R., Ziolkowski A. (2012): Water extractable organic carbon in untreated and chemical treated biochars. Chemosphere, 87: 151–157.

Liu J.Y., Shen J.L., Li Y., Su Y.R., Ge T.D., Jones D.L., Wu J.S. (2014): Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system. European Journal of Soil Biology, 65: 30–39.

Lu R.K. (1999): Analysis Methods of Soil Science and Agricultural Chemistry. Beijing, Agriculture, Science and Technology Press. (In Chinese)

Nunan N., Morgan M.A., Herlihy M. (1998): Ultraviolet absorbance (280 nm) of compounds released from soil during chloroform fumigation as an estimate of the microbial biomass. Soil Biology and Biochemistry, 30: 1599–1603.

Paustian K., Six J., Elliott E.T., Hunt H.W. (2000): Management options for reducing $CO_2$ emissions from agricultural soils. Biogeochemistry, 48: 147–163.

Shaaban M., Peng Q.-A., Lin S., Wu Y.P., Khalid M.S., Wu L., Mo Y.L., Hu R.G. (2016): Dolomite application enhances $CH_4$ uptake in an acidic soil. Catena, 140: 9–14.

Smith P., Martino D., Cai Z.C., Gwary D., Janzen H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes B., Sirotenko O., Howden M., McAllister T., Pan G.X., Romanenkov V., Schneider U., Towprayoon S., Wattenach M., Smith J. (2008): Greenhouse gas mitigation in agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363: 789–813.

Wang J.Y., Song C.C., Hou A.X., Miao Y.Q., Yang G.S., Zhang J. (2014): Effects of freezing-thawing cycle on peatland active organic carbon fractions and enzyme activities in the Da Xing'anling Mountains, Northeast China. Environmental Earth Sciences, 72: 1853–1860.

Wolf B., Zheng X.H., Brüggemann N., Chen W.W., Dannenmann M., Han X.G., Sutton M.A., Wu H.H., Yao Z.S., Butterbach-Bahl K. (2010): Grazing-induced reduction of natural nitrous oxide release from continental steppe. Nature, 464: 881–884.

Wong V.N.L., Dalal R.C., Greene R.S.B. (2008): Salinity and sodicity effects on respiration and microbial biomass of soil. Biology and Fertility of Soils, 44: 943–953.

Wu X., Brüggemann N., Butterbach-Bahl K., Fu B.J., Liu G.H. (2014): Snow cover and soil moisture controls of freeze-thaw-related soil gas fluxes from a typical semi-arid grassland soil: A laboratory experiment. Biology and Fertility of Soils, 50: 295–306.

Yao Z.S., Zheng X.H., Xie B.H., Mei B.L., Wang R., Butterbach-Bahl K., Zhu J.G., Yin R. (2009): Tillage and crop residue management significantly affects N-trace gas emissions during the non-rice season of a subtropical rice-wheat rotation. Soil Biology and Biochemistry, 41: 2131–2140.

Yeboah S., Zhang R., Cai L., Li L., Xie J., Luo Z., Liu J., Wu J. (2016): Tillage effect on soil organic carbon, microbial biomass carbon and crop yield in spring wheat-field pea rotation. Plant, Soil and Environment, 62: 279–285.

Yergeau E., Kowalchuk G.A. (2008): Responses of Antarctic soil microbial communities and associated functions to temperature and freeze-thaw cycle frequency. Environmental Microbiology, 10: 2223–2235.

Zhang A.F., Liu Y.M., Pan G.X., Hussain Q., Li L.Q., Zheng J.W., Zhang X.H. (2012): Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant and Soil, 351: 263–275.

Zhang J., Wang X.J., Wang J.P. (2014): Impact of land use change on profile distributions of soil organic carbon fractions in the Yanqi Basin. Catena, 115: 79–84.

Received on September 19, 2016
Accepted on May 30, 2017
Published online on June 2, 2017