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Five crop seasons' records of greenhouse gas fluxes from upland fields with repetitive applications of biochar and cattle manure

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ABSTRACT

The application of char to agricultural land is recognized as a potential way to sequester atmospheric carbon (C) assimilated by plants in soil, thus decelerating global warming. Such a process would also be expected to improve plant growth and the physical and chemical properties of soil. However, field investigations of the effects of continuous char application have not been reported. In the present study, the effects of repetitive bamboo char application on CO_2, CH_4, and N_2O flux from soil, soil C content, and crop yield were investigated at two upland fields over five crop seasons. Three treatments: chemical fertilizer (CF) applied plots (Control plot); cattle manure (CM) (10 t ha^{-1}) and CF applied plot (CM plot); and bamboo char (20 t ha^{-1}), cattle manure (10 t ha^{-1}), and CF applied plot (Char/CM plot), were arranged in each field. After three crop seasons, the fourth treatment with char was applied without CF (Char plot) was given to one of the fields. CM and/or char were applied every crop season. Gas fluxes were measured using the static chamber method. Seasonal variations in CO_2 flux and total CO_2 emissions were consistently similar between the CM and Char/CM plots and between the Char and Control plots. As such, the decomposition rate of bamboo char was quite small, and the positive or negative effect of char on CM decomposition was not significant in the fields. Soil C analysis provided confirmation of this. CM application enhanced N_2O emission mainly in the summer crop season. The differences in total N_2O emission between the Char/CM and CM plots as well as between the Char and Control plots were insignificant in most cases. Total CH_4 flux was negligibly small in all cases. Although the yield of winter crop (broccoli) in the Char/CM plots was twice observed to be higher than that in the Control and CM plots at one of the fields, in general, the char application had no effect on overall crop yield. Thus, the repeated application of bamboo char had no significant influence on greenhouse gas emissions and crop yields, but a high C accumulating function was found.

1. Introduction

The application of artificially charred biomass (biochar) to soil has recently attracted attention as a way to sequestrate the atmospheric carbon that is assimilated by plants in soil for decelerating global warming (Lehmann et al., 2006; Lehmann, 2007) along with improving the physical and chemical properties of soil (Artiola et al., 2012; Glaser et al., 2002). The former is based on the recalcitrant nature of charred plant fragments in natural soil (Pessenda et al., 2001; Preston and Schmidt, 2006) and buried Anthrosols, such as *terra preta* in Brazil (Glaser and Birk, 2012; Liang et al., 2008).

The occurrence of biochar decomposition in soil at a detectable level has been confirmed using ^{14}C labeled char (Kuzyakov et al., 2009) or based on the difference in $\delta^{13}C$ between biochar and soil organic matter (Knoblauch et al., 2011). The decomposability of biochar has largely been investigated in laboratory experiments; some of which showed no significant increases in CO_2 flux after a biochar was incorporated into soil (Novak et al., 2010). Other studies indicated that biochar undergoes decomposition at a slow rate, e.g., <4.5% during a maximum 3-year incubation period (Kuzyakov et al., 2009; Zavalloni et al., 2011; Zimmerman, 2010), although a considerable amount of corn- and oak-derived char produced at 350 °C and 600 °C (up to 20%) was reported to be lost

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during a 1-year incubation period by Nguyen et al. (2010). The addition of a simple substrate such as glucose can accelerate biochar decomposition (Hamer et al., 2004; Kuzyakov et al., 2009), whereas no effect was observed when a plant residue was simultaneously applied (Novak et al., 2010; Zavalloni et al., 2011). Biochar application may influence the rate of decomposition of other organic materials through their sorption (Lin et al., 2012) and altering microbial activity (Atkinson et al., 2010).

In practical agricultural fields, the fate of biochar is more complex. In addition to biological decomposition and chemical degradation, some of the biochar may be lost to erosion by the action of wind or rain, photochemically degraded, and percolated downward into the soil profile to various extents. However, there are only a few reports dealing with biochar decomposition in agricultural soils based on field experiments (Jones et al., 2012; Kimetu and Lehmann, 2010). Major et al. (2010a) investigated the dynamics of a mango tree char that was produced at 400–600 °C for 48 h in Colombian soil and reported that 2.2% of the char was decomposed over a period of two years with 1% and 20–53% losses by leaching and uncertain causes such as runoff by intense rain, respectively. In their study, the apparent increase in CO_2 flux due to biochar application was larger than the net increase based on biochar decomposition, which was attributed to an increase in crop biomass. Knoblauch et al. (2011) reported that CO_2 emission from a Philippines rice soil with and without rice husk char did not significantly differ from each other.

The influence of biochar application on the flux of other greenhouse gases has also been frequently evaluated in laboratory experiments. For example, Spokas and Reicosky (2009) compared CO_2, CH_4, and N_2O fluxes from three soils with 16 different biochars amended in a 100-d incubation under upland moisture conditions. They reported that, in most cases, the rate of oxidation of CH_4 or the rate of production of CH_4 was decreased and N_2O production was suppressed as the result of the presence of biochar. In a field experiment, Zhang et al. (2012) observed that the application of 20 or 40 t ha^{-1} of wheat straw char (350–550 °C) decreased N_2O emission when N fertilizer was applied, although CO_2 emission remained unchanged. On the contrary, Karhu et al. (2011) reported that there were no significant differences in CO_2 and N_2O fluxes from a Finnish upland field with and without birch char amendment produced at 400 °C at a rate of 9 t ha^{-1}, while CH_4 uptake in the biochar amended soil was almost double of that in the unamended soil.

Various mechanisms for improving crop production by char application have been proposed, including a direct effect as a fertilizer, increasing nutrient use efficiency, enhancing nutrient holding capacity, improving soil physical properties, and modifying soil microbial communities (Atkinson et al., 2010; Sohi et al., 2010). Although Yamato et al. (2006) showed an improvement in soil chemical properties following bark char application (37 t ha^{-1}), such as pH, available P content, cation exchange capacity, base saturation, and exchangeable Al content, the effect of char on the yield of maize, cowpeas, or peanuts was not definitive. Major et al. (2010b) reported that maize grain yield was increased 2–4 years after a single application of 8 or 20 t ha^{-1} of woody char, relative to the control plot, indicating the indirect and continuous effect of char on crop production. These results suggest that monitoring the continuous effect of char amendment on crop yields in an upland field where different crops are cultivated in a rotational manner are needed.

The purpose of the present study was to evaluate the effect of repetitive biochar application on greenhouse gas emissions in some actual farm fields. To guarantee crop production, chemical fertilizers (CF) and/or cattle manure (CM) were also applied, which made it possible to examine the influence of biochar on CM decomposition and vice versa. Variations in CO_2, CH_4, and N_2O fluxes were recorded over five crop seasons in two upland fields under conditions of crop rotation. Changes in soil C content and the yields of each crop were also measured.

2. Materials and methods

2.1. Experimental plots

In January 2010, experimental plots were installed in two upland fields (Fields F and K) located in Obu City, Aichi Prefecture, Japan. Soil type is Dystric Cambisols in both fields. The initial total C content in the plow layer soil (0–20 cm) was 6.3 g kg^{-1} in Field F and 14.1 g kg^{-1} in Field K, which are equivalent to 1.1 and 3.1 kg m^{-2}, respectively. The total N content was 0.7 and 1.6 g kg^{-1} in Fields F and K, respectively. The following three types of treatment plots were prepared in each field: a CF plot (Control plot); CM (10 t ha^{-1} or 2.5 t C ha^{-1}) and CF applied plot (CM plot); and bamboo (*Phyllostachys heterocycla* f. *pubescens*) char (20 t ha^{-1} or 15 t C ha^{-1}), CM (10 t ha^{-1}), and a CF applied plot (Char/CM plot). The plot size in Field F was 2 × 5 m and that in Field K was 1.3 × 5 m. Each type of treatment plot was prepared in triplicate in each field by a randomized design. In Field F, a 1-m width between the plots was left as a buffering area, whereas each plot was surrounded by woody barriers with heights of 12 cm in Field K throughout the experimental period. Compound fertilizer was applied as the CF to all the plots at the same rate (1.2 t ha^{-1}) irrespective of the kind of crop, which corresponded to the applications of N, P, K, and Mg at 144, 31, 79, and 14 kg ha^{-1}, respectively. Nitrogen was applied in the form of urea. The CM used was mature, composted cow manure with 358 g C kg^{-1} and 27.0 g N kg^{-1} on a dry matter basis (C/N ratio, 13.3). The bamboo char used was prepared by heating at 700–800 °C for 25 h in a closed kiln, followed by pulverizing the material to a particle size of <2 mm (total C, 801 g C kg^{-1}; total N, 8.1 g kg^{-1} on dry matter basis). All of the CF, manure, and char were spread by hand and then incorporated into the plow layer (20-cm depth) soil by a chisel plow one day before transplantation in each crop season. A fourth treatment plot (Char plot) with 20 t ha^{-1} of char being applied without CM was installed in Field F at the beginning of the 2011 summer crop season (triplicate), where the same crops had been cultivated with CF applied at the same rate as the other plots.

Crop rotation was as follows: broccoli (*Brassica oleracea* var. *italica*) in 2009 winter season (January 17 2010–April 24 2010), sweet potatoes (*Ipomoea batatas* L.) in the 2010 summer season (June 13 2010–October 22 2010), broccoli in the 2010 winter season (November 8 2010–April 13 2011), and kabocha squash (*Cucurbita*) in the 2011 summer season (May 26 2011–August 24 2011). In the 2011 autumn season, potatoes were transplanted on September 8. However, as it failed to grow, bok choy (*Brassica rapa* var. *chinensis*) was transplanted on October 13 without any further application of CF and organic amendments and without tillage. Bok choy was harvested on December 15 2011. Neither additional fertilizer nor agrochemicals were applied to any crop. At each harvest, the fresh weight of the edible part was measured for 10–20 individuals (same number in the same season) in the field.

2.2. Collection and analysis of gas samples

Gas samples were collected using the static chamber method 3–5 times (days) during 1–8 days after fertilization and at an interval of 7–14 days during the residual crop period and inter-crop periods before the 2010 and 2011 summer crop seasons. A pedestal with a circular dent on the top was installed at the center of each plot at a soil depth of 3-cm on the day of transplantation at a