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Carbon mineralization following additions of fresh and aged biochar to an infertile soil

Rudong Zhao [a], Neil Coles [b], Jiaping Wu [a,*]

[a] Institute of Islands and Coastal Ecosystems, Zhejiang University, Hangzhou 310058, China
[b] Institute of Agriculture, The University of Western Australia, Crawley, WA 6009, Australia

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ABSTRACT

Biochar (BC) aging that has not undergone soil processing before adding to soils may have a different effect on soil carbon (C) mineralization in the short term. This article focuses on studying short-term effects of fresh and aged biochars (without soil processing) on C mineralization in a typical infertile soil in the hilly red soil region of southern China. Tree bark charcoals with known ages of 10 years ($BC_{10years}$) and 4 months ($BC_{4months}$) were collected and fresh biochar (BC_{fresh}) was produced in the laboratory using the same feedstock under similar conditions. A 42 day incubation experiment was conducted with treatments consisting of soil + 2% $BC_{10years}$ (SB10-2), soil + 2% $BC_{4months}$ (SB4-2), soil + 2% BC_{fresh} (SBf-2), soil + 5% BC_{fresh} (SBf-5) and soil only (CK). Treatments with clean quartz sand (with a similar volume) instead of the soil were also conducted. During the incubation, enhanced C released as CO_2 (CO_2-C) was observed in SB4-2, SBf-2 and SBf-5; but not in SB10-2, and no CO_2-C was detected in the quartz sand treatments. Biochar additions increased the C amount in the treated soil. After incubation, minor changes of dissolved organic C were detected after biochar additions. The highest values of dissolved organic nitrogen and ammonium nitrogen were detected in SB10-2. Biochar additions increased microbial biomass C, and pH levels with the highest values recorded in SBf-5 (14.71 mg kg^{-1} and pH 5.30). The results suggest that soil C mineralization can be enhanced by the addition of fresh (BC_{fresh}) or relatively young biochar ($BC_{4months}$), but is not evident when aged biochar ($BC_{10years}$) is added. The biochar, whether newly produced or aged for several months without soil processing, can promote C mineralization of infertile soils in a relatively short time, but this does not appear to be the case for biochar aged for 10 years without soil processing.

1. Introduction

Biochar (BC) incorporation into soils can promote carbon (C) sequestration (Pratt and Moran, 2011; Spokas, 2013) and has been shown to amend infertile soils, ameliorate soil acidity, and improve the availability of soil nutrients (Cui et al., 2011; Nelissen et al., 2012; Xu et al., 2012). The C sequestration potential is attributable to the stability of the C in biochar and the possible suppression effect of biochar on soil C mineralization (Jones et al., 2011), although the C mineralization can be promoted by biochar additions (Luo et al., 2011). The labile C fraction in organic materials is closely related to soil microbial population (Sakamoto and Oba, 1991). This is similar to that in biochar (Smith et al., 2010), which may promote the consumption of soil C (and other nutrients). Soil C, however, may be retained by sorption and physical protection by organic matter due to: (1) the structure and properties of the biochar, i.e., large surface area and porosity (Kasozi et al., 2010; Zimmerman et al., 2011); (2) retention by soil microorganisms due to the texture of soil (Dempster et al., 2012); and (3) the low pH of biochar (Aciego Pietri and Brookes, 2008). After biochar addition, soil microorganism (mass and activity) and thus C mineralization may also vary with soil type, organic C content and nutrient availability, e.g., nitrogen (N) (Kolb et al., 2009; Zimmerman et al., 2011). Thus, both the types of biochar and soil play key roles throughout the alteration processes of soil property (Steinbeiss et al., 2009; Van Zwieten et al., 2010). The extent of C mineralization following biochar addition requires further analysis to determine the interactions between biochar, C mineralization and soil amendments; especially in infertile soils over the short- to medium-term, if the C sequestration potential of biochar addition to soils is to be quantified.

All biochar decays over time, but the rate may vary under different environmental conditions. The labile C fraction decomposition and short-term biochar oxidization occurs via abiotic process in soils (Cheng et al., 2006). This process is more important for effective soil amendment than C sequestration in the short term, as nutrients that include soluble C and N can be released during biochar aging (Abiven et al., 2011). However, this aging process may lead to an increase in surface acidity resulting in a pH decline (Cheng and Lehmann, 2009), which will ultimately result in the suppression of soil microorganism

* Corresponding author. Tel.: +86 571 88982813; fax: +86 571 88208891.
E-mail addresses: rudongzhao@gmail.com, rudongzhao@163.com (R. Zhao), jw67@zju.edu.cn, zhrd255@126.com (J. Wu).

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activity. Microorganism growth and activity are mainly stimulated by changes in soil physicochemical properties (e.g., pH and structure) and the short-term increases in labile C fraction following biochar addition. Biochar also provides nutrient sources and habitat for microorganisms through abiotic disintegration and microbial decomposition in the longer term (Quilliam et al., 2013). However, until now, most studies have focused on the C kinetics of soil and biochar following biochar aging in soils and sediments; few have focused on biochar aging or on biochar that has not undergone soil processing before being added to soils. This may affect soil C mineralization through different mechanisms. For instance, the labile C fractions "disappear" in a relatively short time frame, and thus the mineralized C in soils amended with biochar, may actually originate from stable compounds (e.g., aromatic compounds) over extended time periods (Zimmermann et al., 2012). The process may also involve mechanisms different from those associated with biochar that has not undergone soil processing prior to being added to the soil. Compared to biochar aged without soil processing, biochar aged in soil exhibits stronger oxidization, increased mineral fractions and microorganisms (Hockaday et al., 2007). Therefore, C mineralization in the soil matrix appears to be more dramatic owing to the influence of localized soil processes. Whether biochar aging occurs in soils or not, C mineralization is likely to be minor, relative to the total amount of C (both introduced C and native soil C). Biochar will therefore enhance C sequestration due to the introduction of stable C, and the additional sorption from soil organic matter (Kasozi et al., 2010), and the incorporation of the biochar particles into the soil in the longer term (Eckmeier et al., 2007).

In a number of studies on C mineralization of various organic materials (e.g., biochar, crop waste, animal manure), the application of a double-exponential model has been proven to be valuable (Liang et al., 2008; Molina et al., 1980; Qayyum et al., 2012; Saviozzi et al., 1997). Using a typical infertile cultivated soil and biochar from a local tree species (*Pinus massoniana*) from the hilly red soil region of southern China, the performances of the soil processes and biochar of different ages were assessed. This study focused on the short-term effects of fresh and aged biochar, prior to soil processing, on C mineralization in the infertile soil. In undertaking this study, we hypothesize that (a) the fresh biochar promotes soil C mineralization in the short term; (b) the effect of aged biochar on soil C mineralization decreases over time and (c) the decomposition of the biochar is favorable to soil amendment.

2. Materials and methods

2.1. Study area

Zhejiang Province (27°02′–31°11′N, 118°01′–123°25′E) covers a continental area of about 101,800 km^2 and is located in the hilly red soil region of southern China with a provincial population of approximately 70 million. The climate is classified as subtropical monsoon with a mean annual precipitation of 1300 mm and an average annual temperature of 15–19 °C. The morphology of the landscape is complex and hilly, with 70% of the region above 300 m.

2.2. Sampling

In April of 2012, soil samples from a typical infertile quaternary red soil (Typical Plinthudults, 0–30 cm) were collected from different soil profiles in Jinhua City of Zhejiang Province. This soil type is extensively cultivated in this region and the soil characteristics are shown in Table 1. In the same area, *P. massoniana*-bark charcoal (biochar) was collected from different undisturbed and burnt *P. massoniana* trees. The samples were taken from the top of hills that had been burnt during forest fires in 2001 and 2011. The tree bark biochars were aged (or degraded) in situ and have not come in contact with the soils (i.e., sampled at least 1 m above the soil surface). The fires were started by fireworks on two different hills on exactly the same date (22nd December) of 2001 and 2011, respectively. That is, the biochars have been aged for around 10 years and 4 months, respectively (labeled as $BC_{10years}$ and $BC_{4months}$). For comparison, fresh *P. massoniana* bark was also collected from the living trees near the two sites to generate biochar in the laboratory.

2.3. Biochar preparation

After air-drying and being milled to 1–2 cm^3, fresh *P. massoniana* bark was mixed thoroughly and placed in crucibles covered with lids. The bark was pyrolyzed in a programmed muffle furnace (Shanghai Jinghong Laboratory Equipment Inc., Shanghai, China). The pyrolysis temperature was raised at the rate of 20 °C min^{-1} to the desired value of 450 °C and maintained for 1 h, which is close to the temperature generated by natural fires that produce biochar in the field (Brown et al., 2006; Peng et al., 2011; Wolf et al., 2013). The biochar made from fresh *P. massoniana* bark (labeled as BC_{fresh}) was cooled to room temperature in the furnace without disturbance. After being ground and passed through a 1 mm sieve, the requisite biochars $BC_{10years}$, $BC_{4months}$ and BC_{fresh} were sealed in containers and stored in the dark.

2.4. Biochar characteristics analysis

Volatile matter and ash contents were determined based on a modified ASTM method (D1762-84) (ASTM, 2007) by measuring the weight loss following combustion of about 5.0000 g of biochar. The sample was placed in a ceramic crucible and heated in a programmed muffle furnace at 950 °C for 6 min, and at 750 °C for 6 h, respectively. Concentrations of elemental C, hydrogen (H) and N were detected with an element analyzer (Flash EA 1112, Thermo Finnigan, Italy). All of the concentrations were determined on a dry weight and ash-free basis. Oxygen (O) concentration was calculated using the weight difference assuming that the total weight of the biochars was made up of C, H, N and O only.

A biochar sample was mixed with deionized water (1:5 by wt.:vol.) and stirred for 2 min using an electromagnetic stirrer. After letting the mixture stand for 1 h, the pH was measured using a digital pH meter (Sanxin-MP521, Shanghai Youyi Co., China). The carbonate content in the biochar was measured according to the method described by Yuan et al. (2011). The CO_2 released from the biochar sample (0.154 mm sieve) was measured volumetrically after the addition of a 4 M HCl solution. The results were calculated based on the comparisons of $CaCO_3$ (standard level) dried at 104 °C.

Table 1
Properties for the test soil.

pH	Organic C (g kg^{-1})	Total N (g kg^{-1})	Soil texture (%)		
			Sand 2.00–0.05 (mm)	Silt 0.05–0.002 (mm)	Clay <0.002 (mm)
4.84 ± 0.02	4.20 ± 0.48	0.28 ± 0.01	21.67 ± 0.37	37.00 ± 0.52	41.33 ± 0.18

All values are means of three replicates and standard deviation.