Agriculture, Ecosystems and Environment 239 (2017) 80–89

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Changes in microbial biomass and the metabolic quotient with biochar addition to agricultural soils: A Meta-analysis

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A R T I C L E I N F O

Article history:
Received 28 June 2016
Received in revised form 8 January 2017
Accepted 9 January 2017
Available online 25 January 2017

Keywords:
Biochar
Soil respiration
Microbial biomass
Carbon stability
Microbial activity
Agricultural soil

A B S T R A C T

Biochar has been increasingly recommended for world agriculture, but the effects on microbial activities in agricultural soils has not yet thoroughly assessed. In this study, using a meta-analysis of experiment data retrieved from literature published up to March 1, 2015, changes were examined in microbial biomass and soil respiration in agricultural soils with biochar addition. Microbial responses to biochar addition were quantified in soil respiration quotient (RQ), microbial quotient (MQ) and metabolic quotient (qCO_2) and their differences were evaluated between with and without biochar addition, and among groups of biochar production conditions and experiment conditions. There was an overall increase by 25% in soil microbial biomass carbon (SMBC) and nitrogen (SMBN) but a decrease by 13% in qCO_2, under biochar compared to the control. Whereas, microbial biomass carbon was increased by 26% but total soil CO_2 production unchanged, across all short term experiments up to 6 months following a single biochar addition. A significant reduction (by <20%) in qCO_2 was found under crop residue and manure biochars in term of feedstock, and biochars pyrolyzed at high temperature over 500 °C in term of pyrolysis temperature. Whereas, the reduction was great (by over 30%) both in clay soils and in neutral soils but moderate (by 15%) in soil organic carbon (SOC) depleted soils, respectively in terms of soil texture, reaction and SOC level. Thus, soil conditions exerted great impacts on microbial metabolic quotient changes compared to biochar conditions. Nevertheless, microbial responses to biochar addition to agricultural soils were much uncertain with respect to both biochar and experiment conditions. Long term field experiments are still deserved to monitor soil microbial processes as long as sustainable soil managements are concerned with biochar technology in agriculture.

1. Introduction

Biochar has been generally known as a black mixture of organic materials obtained via pyrolysis of waste biomass (Lehmann and Joseph, 2015). Its production and reuse in agriculture have become an emerging technology for sustainable soil management through recycling biomass waste as soil organic amendment (Cernansky, 2015). Biochar's role has been well recognized in enhancing terrestrial carbon (C) sequestration and greenhouse gas mitigation (Woolf et al., 2010; Sohi, 2012; Smith, 2016) as well as in improving soil fertility and plant productivity (Lehmann, 2007; Jeffery et al., 2011; Liu et al., 2013). Biochar used for amendment has been also well known to improve soil aggregation and soil porosity (Van Zwieten et al., 2010; Jeffery et al., 2011; Soinne et al., 2014; Omondi et al., 2016), playing a role in improving biophysical condition for microbial growth and their performance. All these could potentially affect soil health and ecosystem functions, manipulating soil organic matter decomposition and terrestrial carbon (C) cycling (Trivedi et al., 2013; Bardgett and van der Putten, 2014). However,

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Abbreviations: SR, soil respiration; SMBC and SMBN, soil microbial biomass carbon and nitrogen; SOM, soil organic matter; SOC, soil organic carbon; RQ, respiration quotient; MQ, microbial quotient; qCO_2, microbial metabolic quotient.

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http://dx.doi.org/10.1016/j.agee.2017.01.006
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biochar effects on soil microbial community and the functioning have been poorly assessed (Lehmann et al., 2011, 2015).

With special reference to C sequestration, biochar amendment with addition of exotic carbon substrates, could potentially increase soil respiration (Kuzyakov et al., 2000; Smith et al., 2010). This was often in debt as an issue of potential positive priming of decomposition of native soil organic matter, as observed in forest floor by Zimmerman et al. (2011) or with addition of fresh carbon substrates by Kuzyakov et al. (2009). There were contradictory observations in agricultural soils for soil organic carbon (SOC) storage was enhanced in black carbon rich soils from Amazon (Liang et al., 2010) but mineralization of native SOC promoted in a black carbon added soil (Maestrini et al., 2014a, 2014b). Logically, the long term trajectory of SOC dynamics following biochar addition could be addressed with changes in soil microbial biomass and respiratory activity, which has been considered as indicators of SOC turnover by microbial activity (Anderson, 2003; Schloter et al., 2003; Anderson and Domsch, 2010). While simple measures of SOC level provided the information of changes in the size of soil carbon pool (Mukherjee et al., 2016), measurements of microbial biomass and respiration rates could be used for predicting the efficiency by which microorganisms converted carbon substrates into stable organic carbon in soil (Powlson and Jenkinson, 1981; Schloter et al., 2003; Bastida et al., 2008).

Microbial carbon use efficiency has been generally considered the degree by which soil organic carbon was associated with and utilized by soil microbes. It could be taken as a key measure to understand microbial health with ecosystem succession (Bastida et al., 2008) or under human disturbance or under environmental stresses (Wardle and Ghani, 1995). Thus, the size and activity of microbial biomass and respiration could be linked to SOC dynamics across ecosystems. The earliest and simplest parameter to characterize microbial carbon use efficiency was the microbial quotient (MQ), which was the portion of microbial biomass carbon to total organic carbon pool, ranging from 1% to 5% of SOC (Sparling, 1992). The respiration quotient (RQ) was also commonly used and defined as the respiration rate per unit of SOC (Cook and Allan, 1992; Li et al., 2009). However, the metabolic quotient (qCO_2) considered the respiration rate CO_2-C per unit microbial biomass C (Anderson and Domsch, 1993). Conceptually based on Odum's theory of ecosystem succession, qCO_2 has been widely used as indicator for ecosystem succession (during which it supposedly declines) (Insam and Haselwandter, 1989) and maturity (Anderson and Domsch, 1985). Compared to SOC itself, qCO_2 could be more prompt to short term soil changes. A lower qCO_2 reflected an improved soil biophysical conditions resulted shorty from amended organic matter (Powlson and Jenkinson, 1981), but a higher qCO_2 indicated soil degradation under intensive land use (Masciandaro et al., 1998). Again, an increase of qCO_2 could be interpreted as a positive priming on decomposition of the labile SOC pool in soil, following addition of readily degradable carbon substrates to soil (Kuzyakov et al., 2000). More recently, significant increase in qCO_2 along with a reduction in MQ was reported in a metal polluted rice paddy, which partly explained the reduced SOC storage in the polluted soil (Bian et al., 2015). However, adding relatively inert C, particularly in the form of biochar, could also lead to a lower MQ or RQ of the treated soil. Yet, the parameter of qCO_2 could be considered as a promising indicator for the microbial use of carbon for their energy consumption and thus microbial health in soils (Anderson and Domsch, 1993; Anderson, 2003).

Microbial health and carbon use efficiency changes following a short term biochar addition have been not yet evaluated. The purpose of this study was to examine the biochar effects on soil microbial carbon use efficiency in relation to microbial growth in agricultural soils. With a meta-analysis, we tried to characterize the microbial changes with biochar addition using a number of microbiological parameters derived from experiment data in literature. By this we aimed to address bicohar's role in improving microbial growth and health, which could in turn help to stabilize SOC storage in agricultural soils.

2. Materials and methods

2.1. Data source

We searched literature published since 2001 and up to March 1, 2015 via electronic databases including Wiley-Blackwell, Springer Link, Web of Science, and the Chinese Magazine Network (CNKI). A bulk data base of 550 papers was first created by searching using the key words “biochar” and “soil”, after which the database was further filtered using the individual key words “respiration; mineralization and microbial biomass”. Subsequently; the collected literature was carefully checked to exclude studies conducted with non-agricultural soils. The used biochar could not specified as pure or mixed biochar as detailed information of the applied biochar was not always available in some of the reported experiments.

Among the final literature archive of 97 publications, 69 studies reported soil respiration (SR) (including 30 ones reporting also SOC), 54 reported soil microbial biomass C and/or N (SMBC/N) (including 23 ones also reporting SOC) and 26 reported both SMBC and SR. In these studies, SR was estimated either as the reported total CO_2 evolved or as the sum of individual single measurements CO_2 efflux weighted by time intervals, over a defined period. Totally, 1073 individual data pairs of single biochar treatments with and without biochar, were retrieved and used in this analysis. Some of the reported experiments in the collected literature included also treatments with biochar mixed with other material, which were not included as data pairs used for this study. The established data archive is given in Supplementary information (Table S1).

Used in the meta-analysis were the means and standard deviation (SD) of the measurements of SOC, SR and SMBC/SMBN, and the number of replicates of a data pair with and without biochar in a retrieved study. In case with no numerical data shown, the software program Grafula 3 was used to extract numerical data from figures in a publication. For analyzing factors influencing microbial response to biochar, information of biochar production and soil condition as well as experiment condition were also retrieved and categorized. Soil properties were taken into account including soil pH, texture and SOC level while biochar production conditions including the feedstock and pyrolysis temperature as well as the application rate of biochar used. In addition, information of experiment types (field, pot trial or laboratory incubation) and the time since the biochar had been applied to the soil were also recorded.

2.2. Calculation and data processing

Specific quotients were calculated as follows:

$$RQ = SR/SOC \tag{1}$$

$$MQ = SMBC/SOC \tag{2}$$

$$qCO_2 = SR/SMBC \tag{3}$$

Where, SR is soil respiration in g CO_2-C g^{-1} soil, SOC is the concentration of total soil organic carbon in g C kg^{-1} soil, SMBC is soil microbial biomass C in mg kg^{-1} soil as measured using