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A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment

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Abstract

Purpose Previous studies have found biochar-induced effects on native soil organic carbon (NSOC) decomposition, with a range of positive, negative and no priming reported. However, many uncertainties still exist regarding which parameters drive the amplitude and the direction of the biochar priming.

Materials and methods We conducted a quantitative analysis of 1170 groups of data from 27 incubation studies using boosted regression trees (BRTs). BRT is a machine learning method combining regression trees and a boosting algorithm, which can effectively partition independent influences of various factors on the target variable in the complex ecological processes.

Results and discussion The BRT model explained a total of 72.4% of the variation in soil carbon (C) priming following biochar amendment, in which incubation conditions (36.5%) and biochar properties (33.7%) explained a larger proportion than soil properties (29.8%). The predictors that substantially accounted for the explained variation included incubation time (27.1%) and soil moisture (5.0%), biochar C/N ratio (6.2%), nitrogen content (5.5%), pyrolysis time during biochar production (5.1%), biochar pH (4.5%), soil C content (5.2%), sand (4.7%) and clay content (4.1%). In contrast, other incubation conditions (temperature, biochar dose, whether nutrient was added), biochar properties (biochar C, feedstock type, ash content, pyrolysis temperature, whether biochar was activated) and soil properties (nitrogen content, silt content, C/N ratio, pH, land use type) had small contribution (each < 4%). Positive priming occurred within the first 2 years of incubations, with a change to negative priming afterwards. The priming was negative for low N biochar or in high-moisture soils but positive on their reverse sides. The size of negative priming increased with rising biochar C/N ratio, pyrolysis time and soil clay content, but deceased with soil C/N ratio.

Conclusions We determine the critical drivers for biochar effect on native soil organic C cycling, which can help us to better predict soil C sequestration following biochar amendment.

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1 Introduction

During the last decade, biochar has rapidly gained attention not only from the scientific community but also from policymakers and farmers, due to its multifaceted benefits to agriculture and the environment (Lehmann 2007). Biochar is a carbon (C)-rich product obtained when biomass, such as wood, manure or crop residue, is pyrolysed with little or no available oxygen (Lehmann and Joseph 2009). It has also been referred to as pyrogenic organic matter (Maestrini et al. 2014a) or charcoal (Wardle et al. 2008). Here, we define biochar as a collective group of pyrogenic organic matter applied as a soil amendment. Due to the aromatic nature of C in biochar, it possesses a degree of recalcitrance in soil with mean residence times reported between hundreds to thousands of years (Schmidt et al. 2002; Kuzyakov et al. 2009). This property makes it a valuable tool for soil C sequestration (Lehmann et al. 2006; Woolf et al. 2010; Ciais et al. 2013).

However, the amendment of soil with biochar may also affect the decomposition of native soil organic carbon (NSOC). When biochar addition stimulates NSOC decomposition (i.e. positive priming), its benefit to C sequestration will be partially compromised (Wardle et al. 2008). When biochar reduces NSOC decomposition (i.e. negative priming), its C sequestration potential will be greater than expected (Woolf and Lehmann 2012). Many incubation studies have tested the impacts of biochar on NSOC decomposition, but results have been inconsistent. Positive priming of NSOC (Wardle et al. 2008; Luo et al. 2011), negative priming (Jones et al. 2011; Lu et al. 2014b), and no effect (Santos et al. 2012; Nguyen et al. 2014) have been reported. Previous incubation studies reported that biochar priming was affected by factors including biochar properties such as pyrolysis temperature and feedstock type (Zimmerman et al. 2011; Singh and Cowie 2014), soil properties such as pH (Luo et al. 2011) and C content (Stewart et al. 2013) and incubation conditions including soil moisture (Yu et al. 2013) and soil temperature (Fang et al. 2015). However, many uncertainties still exist on the parameters driving the amplitude and the direction of the biochar priming (Maestrini et al. 2014a). Apparently, a synthesis of the data from published papers and a comprehensive understanding of the relation between biochar-induced soil C priming and its determining factors are needed. Although two recent meta-analyses have summarized the influencing factors for biochar effect on NSOC decomposition (Maestrini et al. 2014a; Wang et al. 2015), they neither included incubation conditions (e.g. incubation temperature and moisture) nor compared the importance of the factors for driving the biochar-induced C

priming. Moreover, there are many new empirical papers published in recent years that need to be incorporated to the database to give an updated result.

In this study, we conducted a synthesis to analyse 1170 groups of data from 27 controlled incubation studies. The data included NSOC decomposition rates, under the treatments of biochar amendment and without biochar amendment, and corresponding soil properties (land use, clay, silt and sand content, pH, soil organic C (SOC) and soil total nitrogen (STN) content and C/N (nitrogen) ratio), biochar properties (feedstock type, pyrolysis time and temperature, activation, pH, C and N contents, C/N ratio, ash content) and incubation conditions (temperature, moisture, incubation time, biochar dose and mineral nutrient addition). The aim is to determine the critical factors driving the amplitude and the direction of the biochar priming on NSOC decomposition in well-controlled incubation studies.

2 Material and methods

2.1 Data collection

We performed a systematic literature search of peer-reviewed publications on the effect of biochar addition on NSOC decomposition using the Web of Science database. The cut-off date was 15 August 2017. We collected data from studies that provide NSOC decomposition rates in soils with biochar amendment and without biochar amendment (control), according to the following criteria: (1) We only chose incubation studies rather than field studies, because in the field, it may have higher soil moisture or temperature in the biochar treatment than in the control (Lu et al. 2014a; Malghani et al. 2015; Ventura et al. 2015), impacting observed results for biochar-induced C priming; (2) C isotope (^{13}C or ^{14}C) of emitted CO_2 must be measured, so it can differentiate the quantity of CO_2 derived from biochar and from NSOC; (3) the incubated biochar-amended soil must be without growing plants and without further organic material addition; (4) when the soil was incubated with mineral nutrient addition, similar mineral treatments were required between biochar amendments and controls; (5) the soil must experience the process of pedogenesis, so the data for loess (like soil parent material) in Kuzyakov et al. (2009) was excluded; (6) biochar must be unprocessed other than by activation (partial gasification with steam) and produced under zero or limited oxygen conditions enabling better understanding and replication of the properties of the biochar that impact priming. Thus, the data for (1)

artificially weathered biochar described in Naisse et al. (2015b), (2) biochar with DOC extracted in Whitman et al. (2014), (3) hydrothermal biochar in Naisse et al. (2015b)) and (4) char produced under full atmosphere (enough oxygen) in Zimmerman et al. (2011) were excluded.

Subsequently, in order to take into account the effect of incubation time on the biochar-induced priming, we extracted the paired data of NSOC decomposition rates of biochar treatment (X_e) and control (X_c) at different sampling dates from text, tables or figures in the collected studies. The data presented in figures were obtained using OriginPro 7.5 software (OriginLab, Northampton, MA, USA) with the 'Digitize. OPK' plug-in. The procedure may result in the collected data including more data points from some studies with multiple sampling times than other studies with a few sampling times. However, it will not bring different weights between these two types on the relation between the biochar-induced soil C priming and predictors, since the points for multiple sampling times in the same treatment have the same property for a given predictor (expect for incubation time). Moreover, our data collection could mean that more than one experimental treatment was compared to the same control. In these instances, it artificially increased the number of replicates and may bias the results towards overconfidence (i.e. confidence intervals may be too narrow). However, the more conservative approach of using only a single average measurement for the different measures will sacrifice too much information (Sagrilo et al. 2014).

Some studies directly provided decomposition rates of NSOC under biochar amendment and control (Jones et al. 2011; Zimmerman et al. 2011; Santos et al. 2012; Fang et al. 2014; Lu et al. 2014b). However, most of the studies did not report them directly, so we performed data transformations. Some studies showed the total CO_2 emission in the biochar treatment and CO_2 amount derived from biochar (Kuzyakov et al. 2009; Keith et al. 2011; Naisse et al. 2015a), and the decomposition amount of NSOC was calculated by the difference. Some studies showed the cumulative CO_2 emission derived from NSOC under different incubation stages (Cross and Sohi 2011; Keith et al. 2011; Bruun and El-Zehery 2012; Singh et al. 2012; Maestrini et al. 2014b; Whitman et al. 2014; Dharmakeerthi et al. 2015; Rittl et al. 2015; Cui et al. 2017). X_e and X_c were calculated using the following equation:

$$X_e \ or \ X_c = (CO_2\_C_{n+1} - CO_2\_C_n)/t \tag{1}$$

where $CO_2\_C_{n+1}$ and $CO_2\_C_n$ are the cumulative CO_2-C production derived from NSOC at the $n + 1$th and nth sampling campaigns, respectively, and the value of t is the interval time between the two sampling campaigns.

Some studies showed the remaining NSOC at different incubation durations (Nguyen et al. 2014), and it was calculated by

$$X_e \ or \ X_c = (SOC_{n+1} - SOC_n)/t \tag{2}$$

where SOC_n and SOC_{n+1} are the amount of remaining NSOC at the nth and $n + 1$th sampling campaigns.

Some studies showed priming as $(X_e - X_c)/X_c$ (Luo et al. 2011; Farrell et al. 2013; Herath et al. 2015), and we set X_c as 1 and then calculated the value of X_e. When showing priming as $X_e - X_c$ (Naisse et al. 2015b; Yousaf et al. 2017), X_e was calculated by the addition of X_c. For other cases (Murray et al. 2015; Kerré et al. 2016; Sheng et al. 2016; Luo et al. 2017), it was calculated by the combination of the above equations. If we were unable to calculate X_e and X_c, the study was excluded from data collection. In total, we collected 1196 pairs of data (X_e and X_c) across 27 studies.

In addition to X_e and X_c, the corresponding soil properties (SOC, STN, C/N ratio, pH, clay, silt and sand contents and land use), biochar properties (feedstock type, pyrolysis temperature, pyrolysis time, whether biochar was activated, C and N content, C/N ratio, pH and ash content) and incubation conditions (incubation temperature, incubation soil moisture, incubation days, biochar dose and whether nutrient was added) were also collected. SOC and STN ranged from 2 to 114 and from 0.4 to 10 g/kg, respectively. Soil C/N ratio ranged from 7.7 to 20.2. Soil pH ranged from 3.7 to 8.8. Soils were under five types of land use, including cropland, fallow, grassland, forest and wetland. Pyrolysis time and temperature of producing biochar ranged from 0.025 to 48 h and from 300 to 1200 °C. Biochar C and N contents ranged from 16.5 to 83.9% and from 0.09 to 6.29%, respectively. Biochar C/N ratio ranged from 8 to 344. Biochar pH ranged from 3.90 to 11.21. Biochar ash content ranged from 3.0 to 57.2%. Incubation temperature ranged from 20 to 60 °C, and soil moisture ranged from 40 to 80% water-holding capacity (WHC), except for some data expressed as water potential or water-filled pore space (WFPS). The incubation time, attributing to the last day of a corresponding cumulative period, ranged from 0 to 2551 days. Biochar was applied between 0.07 and 20% (as dry soil weight equivalents).

2.2 Data analysis

The effect size (ES) for each paired observation was calculated as the natural log of the response ratio as

$$ES = Ln \ (X_e/X_c) \tag{3}$$

Thus, positive ES indicates an enhancement of NSOC decomposition following biochar amendment, whereas negative ES means the decrease of NSOC decomposition. The data of ES outside of three standard deviations of its mean, 26 values

totally, were considered outliers and discarded. There were remaining 1170 groups of data (see Online Resource 1 in the Electronic Supplementary Material).

To partition independent influences of soil properties, biochar properties and incubation conditions, we used boosted regression trees (BRTs). BRT is an advanced form of machine learning method that combines regression trees and boosting algorithm (De'Ath 2007). In BRT, multiple trees are fitted and combined in a forward stage-wise procedure to predict the response of the dependent variable to multiple predictors (De'Ath 2007). BRT can simultaneously handle explainable variables of categorical and continuous types that avoids the errors introduced by artificial categorization in the common meta-analysis and does not require the distributional characteristics of the data (Nguyen et al. 2016). Further, BRT can handle missing values in predictors on the basis of 'surrogate' splitting (Zhang et al. 2015). In addition, the independence of predictors is not required in BRT because the interactions of predictors are modelled automatically by the hierarchical structure of a tree (Zhang et al. 2015). Due to the above advantages, the BRT model has been applied effectively in many ecological or environmental studies (Zhang et al. 2012, 2015; Nguyen et al. 2016).

BRT models were operated in R (version 2.15.2; R Development Core Team 2012) by using the gbm package (Elith et al. 2008). In the current BRT analysis, the Gaussian error structure was chosen for the loss function because of the attribution of our response variable (Zhang et al. 2012). There are four input settings for BRT models: (1) the learning rate determines the contribution of each tree to the growing model; (2) the tree complexity controls the level of interactions in BRT; (3) the bagging fraction sets the proportion of observations used in selecting variables; and (4) the cross-validation specifies the number of times to randomly divide the data for model fitting and validation (De'Ath 2007). To find the optimal settings, we fitted 27 BRT models with the combinations of the following settings: learning rates of 0.01, 0.005 and 0.001; bag fractions of 0.4, 0.5 and 0.6; 5-, 8- and 10-fold cross-validations; and a tree complexity of 4 to account for potential high interactions. Among the fitted models, the best model had a cross-validation deviance of 0.081 (± 1 stand error = 0.005) from a learning rate of 0.05, bag fraction of 0.6 and 10-fold cross-validation. The subsequent models were all fitted with these optimal settings. The percentage of variation in ES explained by the BRT model was calculated as $\{1 - [(\text{sum of squared residuals from a BRT model})/(\text{sum of squared residuals from an intercept-only model})]\} \times 100\%$, where 'residuals' refer to test sample residuals (Robinson 2008). We also examined the relative influence of predictor variables to quantify the importance of predictors on the priming effect. The influence of each predictor is based on the number of times for which a variable is selected for splitting, weighted by the squared improvement to the model as a result

of each split and averaged over all trees. Then, the relative importance is scaled such that the sum is 100, and higher numbers correspond to a stronger influence on the priming effect. The net effects of predictors on priming effect average out the effects of the other predictors included in the BRT model and are visualized in partial dependence plots. Moreover, we used a bootstrap technique to estimate the 95% confidence intervals (CI) around each variable, as the BRT cannot directly provide them. According to Carslaw and Taylor (2009), the estimation process was conducted by taking a random sample (with replacement) of the full hourly data set to generate 500 bootstrap replicates. A BRT model was fitted to each sample and predictions made for each variable in turn as described previously. These data are sorted in descending order for each variable and approximate $100 \times (1 - 2\alpha)\%$ confidence limits calculated.

3 Results

The BRT model explained in total 72.4% of the ES variation. Incubation conditions contributed 36.5% of the explanation for the variation of ES, wherein 27.1% was derived from incubation time, 5.0% from incubation moisture and the remaining 4.4% from incubation temperature, biochar dose and nutrient addition (Fig. 1). The ES decreased across the period from 0 to 206 days, increased to a peak at 773 days, then sharply decreased until 1185 days and remained relative stable following that time (Fig. 2a). The ES value decreased with soil moisture, being positive at the range of 40–57% WHC and negative from 57 to 70% WHC (Fig. 2b). The ES value slightly decreased from an incubation temperature of 20 to 50 °C (Fig. 2c). The ES value was larger for < 7.5% w/w biochar dose than > 7.5% w/w dose (Fig. 2d). Nutrient addition did not change the ES value (Fig. 2e).

Biochar properties contributed 33.7% of the explanation, wherein 6.2% was from the biochar C/N ratio, 5.5% from biochar N content, 5.1% from pyrolysis time and 4.5% from biochar pH (Fig. 1). In contrast, other biochar properties, i.e. feedstock type, ash content, pyrolysis temperature and whether biochar was activated, independently contributed < 4%, indicating that they are not relatively important to explain the variation of biochar effect on NSOC decomposition. The ES value continually decreased with biochar C/N ratio (Fig. 3a). Correspondingly, the ES values generally increased with biochar N content, being negative when biochar $N < 3.8\%$ but positive when biochar $N > 3.8\%$ (Fig. 3b). The ES value continually decreased with increasing duration of pyrolysis from 0.025 to 9 h, being constant after 9 h (Fig. 3c). The ES value kept constant during the range of biochar pH from 3.9 to 8.0, then slightly decreased from 8.0 to 10.6, but increased when biochar pH > 10.6 (Fig. 3d). In contrast to the relationship between ES and biochar N content, the ES value decreased
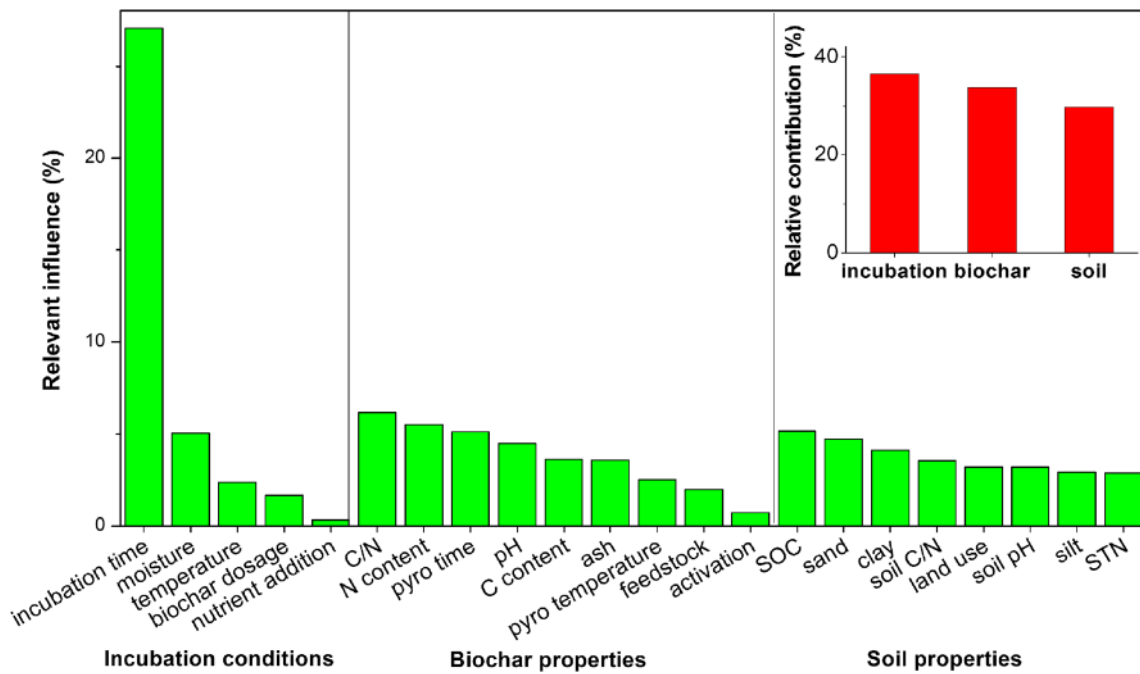
Fig. 1 Percentage relative influence of factors on the priming effect following biochar amendment. The inner figure showed the comprehensive influence of incubation conditions, biochar properties and soil properties

with increasing biochar C, being positive at low biochar C content (< 37.6%) but negative at high biochar C content (> 37.6%, Fig. 3e). The ES value did not change with increasing biochar ash content (Fig. 3f). The ES value decreased when biochar-derived pyrolysis temperature rose from 325 to 600 °C and kept almost constant after that (Fig. 3g). Among the five feedstocks, only sludge-derived biochar resulted in a significant

positive priming and tree- and crop residue-derived biochar showed the lowest ES value, i.e. the largest negative priming (Fig. 3h). Biochar with activation had similar ES with biochar without activation (Fig. 3i).

Compared with incubation conditions and biochar properties, soil properties had a smaller contribution (29.8%) to the explained variation (Fig. 1). Among the soil properties, SOC was the largest contributor

Fig. 2 Partial dependence plots showing the variation in biochar priming effect by incubation condition variables used in the BRT model. **a** Incubation time. **b** Incubation soil moisture. **c** Incubation temperature. **d** Biochar dose (% dried soil weight). **e** Nutrient addition or not. The fitted function shows the relationship between ES and an explanatory variable while all other explanatory variables are kept constant at their mean level. The shading shows the 95% confidence intervals estimated, and the vertical bars show the standard deviations, from 500 bootstrap samples of the data set. The horizontal dashed line represented a predicted ES value equal to 0
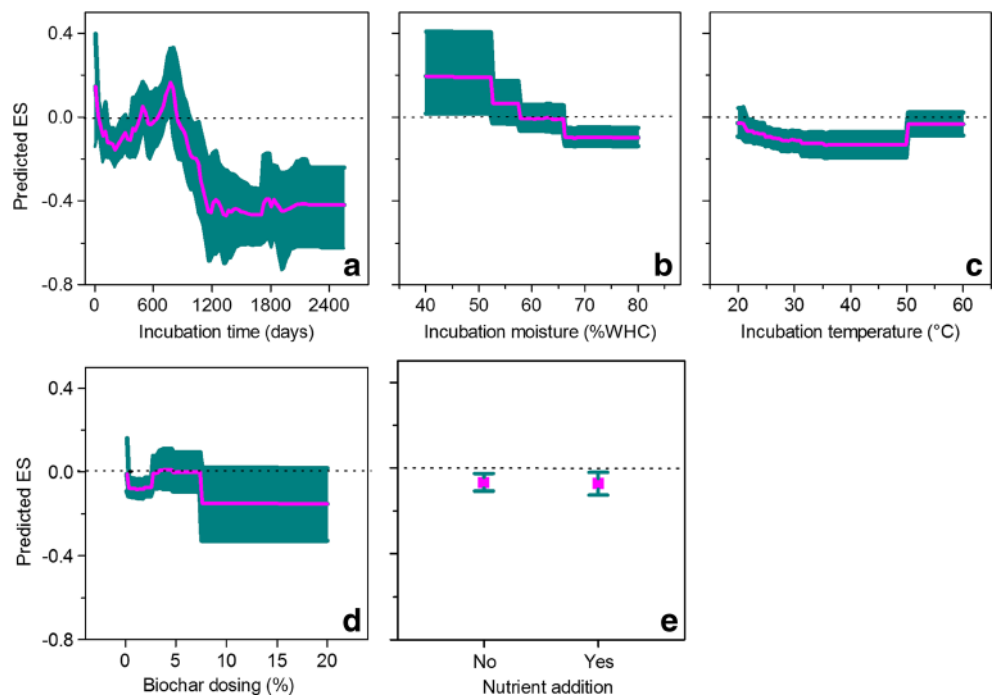
Fig. 3 Partial dependence plots showing the variation in biochar priming effect by biochar properties used in the BRT model. **a** C/N ratio. **b** Biochar nitrogen content. **c** Pyrolysis time during biochar production. **d** Biochar pH. **e** Biochar carbon content. **f** Ash content. **g** Pyrolysis temperature during biochar production. **h** Feedstock types. **i** Whether biochar was activated. The fitted function shows the relationship between ES and an explanatory variable while all other explanatory variables are kept constant at their mean level. The shading shows the 95% confidence intervals estimated, and the vertical bars show the standard deviations, from 500 bootstrap samples of the data set. The horizontal dashed line represented a predicted ES value equal to 0
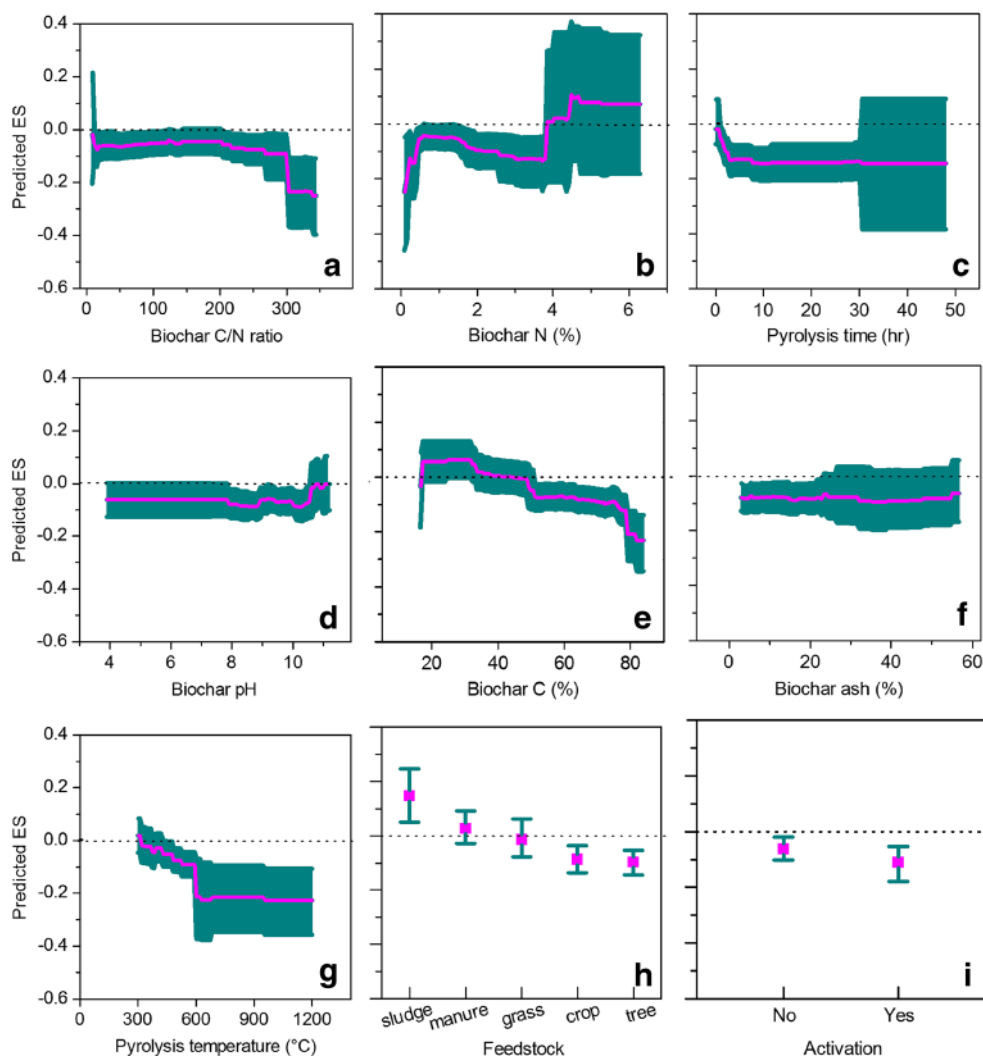

(5.2%), and then it was sand content (4.7%) and clay content (4.1%). The other soil properties had minor contributions, with soil C/N ratio (3.6%), land use (3.2%), soil pH (3.2%), silt content (2.9%) and STN (2.9%). The ES value was positive when SOC <4 g/kg, but sharply decreased to − 1 when SOC = 4 g/kg and then kept generally constant after that (Fig. 4a). The ES value increased with sand content from 4 to 35%, then kept constant from 35 to 60%, but decreased when sand content was larger than 60% (Fig. 4b). In contrast, the ES value changed slightly with clay content from 1 to 54% but continuously decreased when clay content was larger than 54% (Fig. 4c). Notably, the ES value increased with increasing soil C/N ratio (Fig. 4d). The soils under different land uses had similar ES values (Fig. 4e). The ES generally decreased with increasing soil pH (Fig. 4f). The ES value had a slight decline with silt content (Fig. 4g) and increased faintly with STN content (Fig. 4h).

4 Discussion

We identified incubation time as the largest determining factor on biochar-induced C priming. The positive priming only occurred within the first 775 days of incubation, shifting towards negative priming afterwards (Fig. 2a). It was noted that the number of data points for incubation periods greater than 2 years was smaller than shorter-term incubations. Nevertheless, the trend of negative priming upon ageing in soil is supported by many other studies (Zimmerman et al. 2011; Maestrini et al. 2014a, b; Whitman et al. 2014; Weng et al. 2017). Moreover, a recent meta-analysis showed an average negative priming of 3.8% on NSOC decomposition (Wang et al. 2015). These results demonstrated that biochar amendment has the potential to increase non-biochar-derived soil C stocks, especially over a longer term. The possible mechanism for positive priming during early incubation is that labile C within biochar can serve as an energy source for soil microorganisms and stimulate microbial activity shortly after

Fig. 4 Partial dependence plots showing the variation in biochar priming effect by soil properties used in the BRT model. **a** Soil organic carbon (SOC) content. **b** Sand content. **c** Clay content. **d** Soil C/N ratio. **e** Land uses. **f** Soil pH. **g** Silt content. **h** Soil total nitrogen (STN) content. The fitted function shows the relationship between ES and an explanatory variable while all other explanatory variables are kept constant at their mean level. The shading shows the 95% confidence intervals estimated, and the vertical bars show the standard deviations, from 500 bootstrap samples of the data set. The horizontal dashed line represented a predicted ES value equal to 0
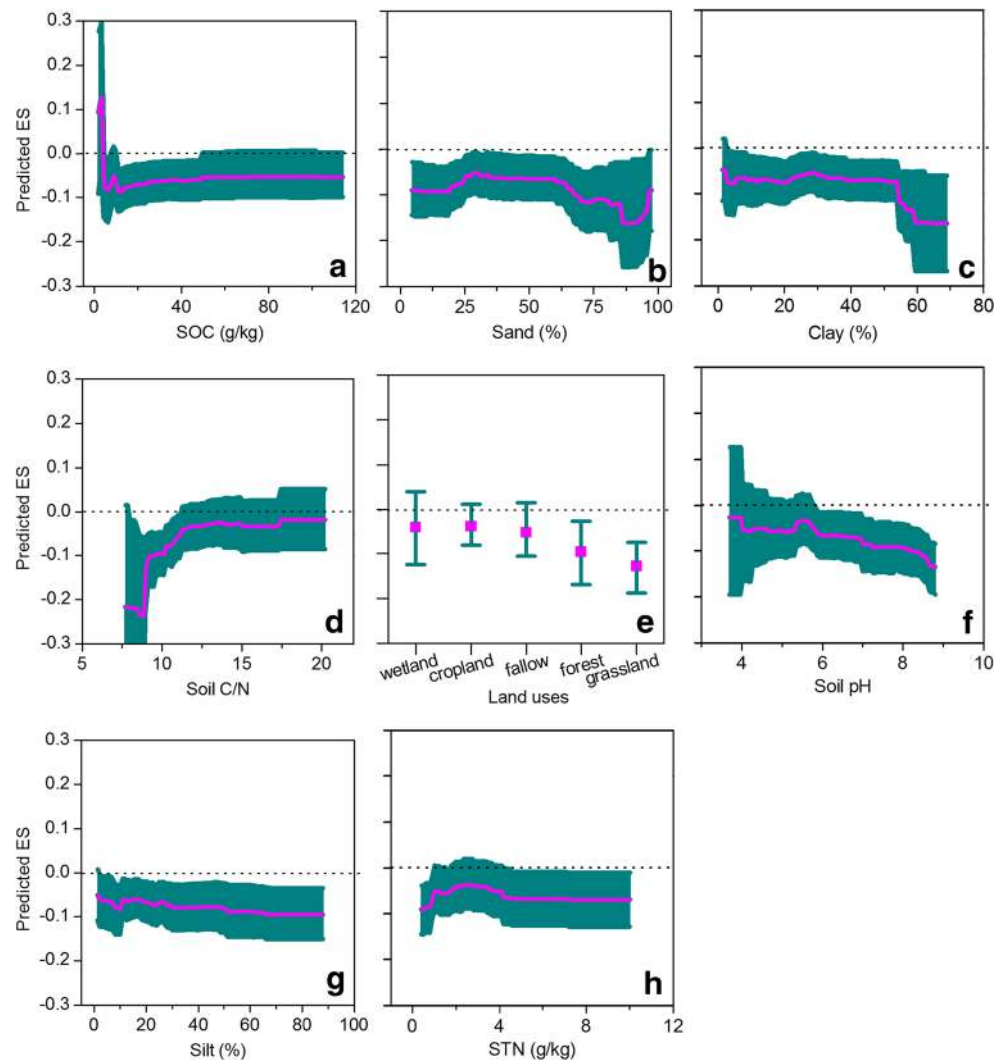
amendment (Lehmann et al. 2011; Weng et al. 2015), but as the labile C depletes during the incubation, microbial stimulation may cease (Table 1). Further, sorption of soil organic matter by the amended biochar has been shown to be kinetically limited by the slow diffusion into the sub-nanometre pores dominating biochar surfaces (Kasozi et al. 2010) and the quantity of NSOC sorbed increased with incubation time, thus resulting in negative priming upon ageing.

Apart from incubation time, incubation soil moisture was an important factor driving biochar-induced priming. Biochar showed positive priming in low-moisture soils but showed a negative one in high-moisture soils (Fig. 2b). The possible mechanism is that biochar may sorb large amounts of soluble NSOC due to its rising mobility in high-moisture soils. This also can explain why Yu et al. (2013) observed smaller biochar-induced positive priming under 85 or 100% WFPS than under 30 or 60% WFPS. Moreover, biochar-induced priming varied with other incubation conditions, although they contributed less to the variation of ES. Greater negative priming was shown at higher soil incubation temperatures up

to 50 °C (Fig. 2c). This was supported by the results of Fang et al. (2015) who observed increasing biochar-induced negative priming from 20 °C incubation to 40 °C incubation in four contrasting soils. Fang et al. (2014) suggested that NSOC molecules in soil water may become more flexible and slowly access interior pores of biochar at higher incubation temperature and thus limit accessibility to soil microorganisms. Only a single study examined incubation temperatures above 50 °C (Fang et al. 2014) thus limiting the information available for the meta-analysis.

Among the biochar properties, biochar C/N ratio was the largest determining factor for the C priming (Fig. 1). The decline of ES with increasing biochar C/N ratio (Fig. 3a) was possibly related to the influence of biochar N and C contents on ES. The priming being negative for low N biochar but positive for high N biochar was probably because high N biochar may supply available N to soil microorganisms in the short term and stimulate microbial activity (Table 1). It was previously assumed that biochar N had low availability due to it being in heterocyclic structures (Knicker and

Table 1 The occurring conditions and possible mechanisms for positive and negative priming on native soil organic carbon decomposition following biochar amendment

Biochar	Occurring conditions	Possible mechanisms
Positive priming	Early incubation, low C biochar, sludge-derived biochar	A large amount of labile C that stimulates microbial activities
	High N biochar	Available N supply stimulates microbial activities
	Low soil moisture	Low mobility of NSOC molecules to be hardly adsorbed by biochar
	Low-C soil	Small amount of dissolved NSOC molecules to be hardly adsorbed by biochar
Negative priming/-large negative priming	Late incubation	Kinetically limited adsorption and labile carbon depletion in biochar
	Large biochar dose	Many sorption sites in biochar that can absorb a large amount of NSOC molecules
	Long pyrolysis time, high pyrolysis temperature, wood-derived biochar	Large biochar surface area and porosity that can absorb a large amount of NSOC molecules
	High-pH soil	Deteriorated soil environment that inhibits microbial and enzyme activities
	High-clay soil	Conducive to formation of soil aggregates which protect NSOC molecules
	Low-C/N soil	Microbes with no lack of N nutrient do not need to decompose NSOC to obtain N

Skjemstad 2000). However, a study using ^{15}N labelling showed that a portion of the N within N-rich biochar is available and easily incorporated by soil microbes and plant biomass (Rosa and Knicker 2011). Even if N in biochar is occluded in aromatic structures, a small amount of N was found to be mineralized (Schouten et al. 2012). Contrastingly, the priming was positive for low C biochar but negative for high C biochar. This can be explained that low C biochar usually contains a larger labile C fraction (Singh et al. 2012), which can simulate microbial activity (Luo et al. 2013).

Other biochar properties also influenced the C priming. Pyrolysis time for biochar production was an important factor for the C priming (Fig. 1). Biochar derived after longer pyrolysis time showed a larger negative priming (Fig. 3c). This

could be explained by the fact that surface area and porosity of biochar increase with pyrolysis time (Chen et al. 2008; Yuan et al. 2014; Zhang et al. 2015), thereby facilitating the greater adsorption of NSOC. This explanation for the results of high larger negative priming for biochar derived from higher pyrolysis temperature (Fig. 3g) was similar, as the sorptive capacity of biochar also increases with pyrolysis temperature (Kasozi et al. 2010). Moreover, biochar pH was an influencing factor for C priming (4.5% contribution, Fig. 1). There was a trend towards weaker negative priming when pH was larger than 10.7 (Fig. 3d). However, the data points within this range were extracted from only two studies, thus limiting the information available for the meta-analysis. In addition, biochar-derived C priming varied with the type of feedstock. Tree- and crop residue-derived biochar had a greater negative priming effect than biochars derived from other feedstock (Fig. 3h). Zimmerman et al. (2011) also observed that tree wood biochar gave greater negative priming than grass biochar. The possible mechanism is that woody biochar generally has a higher surface area and porosity (Hilscher et al. 2009; Lehmann and Joseph 2009; Zimmerman 2010). Contrastingly, sludge-derived biochar showed positive C priming (Fig. 3h). This was likely due to its greater labile C content than other feedstock (Singh et al. 2012). This was partly supported by McBeath and Smernik (2009) who reported that the biochar derived from paper mill sludge had smaller proportion of aromatic (stable) C than the biochars derived from other feedstock, e.g. wood, straw or manure.

Soil properties can also influence biochar-derived C priming. First, SOC content was an important factor for C priming (Fig. 1). The biochar-derived priming was positive in the low-C soils but negative in the high-C soils, which was similar with Maestrini et al. (2014a) who found that the size of the negative PE was higher when the soil had a higher content in C. The possible reason was that low-C soils usually have a small amount of dissolved NSOC molecules that were hardly adsorbed by biochar, thereby impossibly resulting in negative priming and vice versa. Furthermore, soil texture was an influencing factor on biochar effect on NSOC decomposition (sand and clay giving 4.7 and 4.1% contributions, respectively, Fig. 1). Soils with higher clay content had larger negative priming (Fig. 4c). Similarly, Wang et al. (2015) observed a trend of positive priming in soils with a clay content < 10% while negative priming was observed when clay content was > 10%. The possible mechanism was that large amount of clay can encourage the formation of stable soil aggregates (< 250 μm) via organo-mineral interactions between native and/or added organic matter and soil minerals (Golchin et al. 1994; Wagner et al. 2007), thereby protecting NSOC from decomposition (Brodowski et al. 2006; Joseph et al. 2010; Zimmerman et al. 2011).

Biochar-derived C priming also varied with other soil properties, although they contributed little to the explanation for

ES. For example, the size of negative priming decreased with soil C/N ratio (Fig. 4e). The reason could be that microorganisms in soils with high C/N ratio was lacking N nutrient, so they could need to decompose the native SOM more intensely to obtain available N for growth (Zhang et al. 2013), thereby resulting in low net negative priming. Another factor was soil pH. Larger negative priming in alkaline soil was observed than in acidic soil (Fig. 4h). Acidic soils may have less pH-related constraints to microbial activity after biochar amendment (Van Zwieten et al. 2010), but alkaline soil may become more alkaline and suppress soil microbial activity, thereby triggering larger negative priming.

Our results showed that incubation conditions and biochar properties played more important roles in driving biochar-induced soil C priming than soil properties (Fig. 1). This seemed to be different from the drivers for the soil C priming induced by fresh organic materials (no charred). Previous meta-analyses have shown that the priming of NSOC decomposition by fresh organic material was closely related to soil parameters (e.g. SOC, STN, soil C/N ratio or soil clay content and land use type) rather than the properties of the added materials (Zhang et al. 2013; Luo et al. 2016). This difference in drivers could be due to the sorption of NSOC by biochar, as a main mechanism for the negative C priming as discussed in Maestrini et al. (2014a), which is yet unlikely to occur after fresh organic matter addition.

Although our analysis provides new insights into the response of NSOC decomposition to biochar amendment, several knowledge gaps are still apparent. Firstly, the duration of biochar-induced negative priming was evident for 7 years in our meta-analysis. Further, negative priming has been detected a decade after biochar was applied to a ferrosol under subtropical pasture (Weng et al. 2017), indicating the potential for biochar amendment to support soil C sequestration beyond the stable C content of biochar alone. However, a paucity of longer-term studies (lasting for decades) using C isotope differentiation between biochar C and NSOC remains, especially under varying soil types and climatic conditions. Considering biochar would persist in soils on a centennial scale (Wang et al. 2015), future studies need to test whether the negative priming of biochar can last for so long.

5 Conclusions

Our synthesis critically evaluated the influencing factors on the biochar-induced soil C priming in laboratory settings. We demonstrated that biochar properties and incubation conditions have larger impacts on the priming than soil properties. We also identified the factors (> 4% contribution) driving biochar-induced priming in incubation studies, these being incubation time and soil moisture, biochar C/N ratio and N content and pH, pyrolysis time during biochar production and

SOC content and soil texture. We revealed that biochar amendment showed positive priming during early incubation, for the biochars with low C content or high N content or derived from sludge and in the soils with low C content or with low moisture. In the other circumstances, it would show negative priming. These insights can help us to better predict the effect of biochar amendment on soil C cycling.

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