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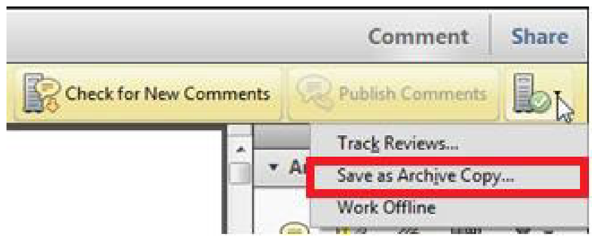

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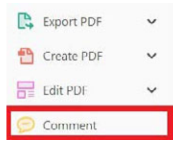

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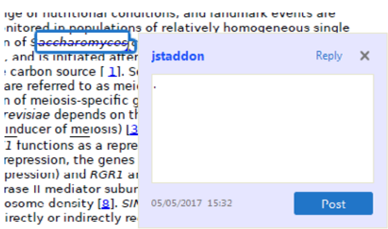

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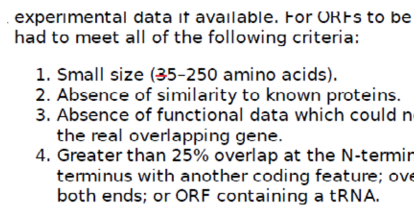

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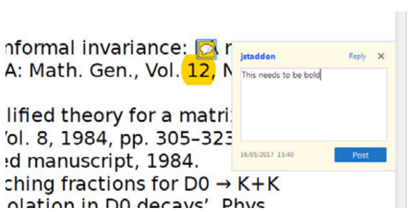

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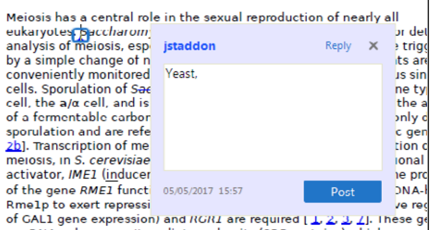

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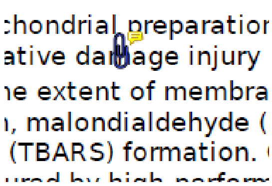

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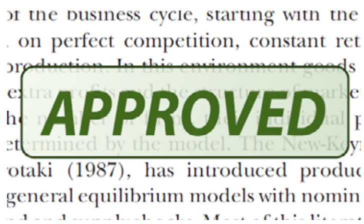

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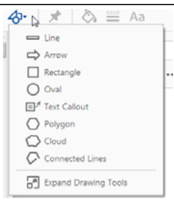

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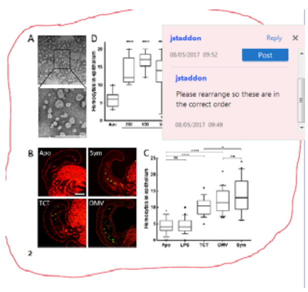

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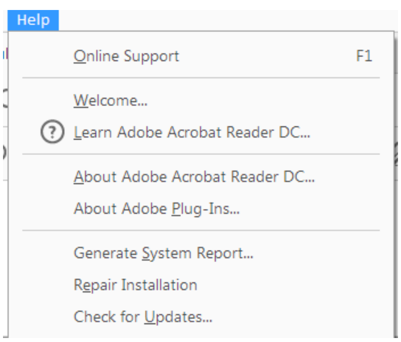

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Understanding the dominant controls on biochar decomposition using boosted regression trees

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Summary

Extensive studies have been carried out to investigate the decomposition of biochar. Biochar properties, soil characteristics and incubation conditions are considered key factors that control the rate of biochar decomposition. However, the relative contributions of these factors to its decomposition remain unknown. Approximately 812 individual measurements of the rate of biochar decomposition were collected from 23 studies involving ^{13}C or ^{14}C isotope techniques to evaluate the effects of incubation conditions, soil characteristics and biochar properties on its decomposition with a boosted regression tree (BRT) model. The BRT model accounted for 95% of the variation in biochar decomposition. Incubation conditions, soil characteristics and biochar properties accounted for 41, 31 and 28% of variation in the rate of biochar decomposition, respectively. The most important single predictor of biochar decomposition was incubation time (contributing 33% to the rate), followed by soil carbon: nitrogen (C:N) ratio (9%), pyrolysis time (9%), soil N content (8%) and biochar C content (7%). The rate of decomposition of biochar decreased with time for incubation times less than 1 year. Soil with a large C content and a small C:N ratio resulted in a large rate of biochar decomposition. Type of feedstock and biochar N content had little or no effect on biochar decomposition. Our results provide further insight into the factors that affect biochar decomposition and quantify the relative contributions of these factors to it.

Highlights

- We studied the dominant factors that control biochar decomposition with BRT modelling.
- We quantified relative contributions of incubation conditions, soil characteristics and biochar properties to biochar decomposition.
- Rate of biochar decomposition explained by incubation conditions (41%), soil characteristics (31%) and biochar properties (28%).
- The most important predictor of biochar decomposition was incubation time.

Introduction

Biochar is the charred residue of the incomplete combustion of plant materials and fossil fuels, and can comprise up to 5–45% of global soil organic carbon (SOC) (Bird *et al*., 2015; Santín *et al*., 2016). In recent years, biochar has been extensively investigated because of its importance in the terrestrial carbon (C) cycle. It contains very condensed polycyclic aromatic structures that can resist degradation and persist in soil for decades to centuries (Bird *et al*., 2015). Therefore, adding biochar to soil is a promising strategy for offsetting the release of greenhouse gases to the atmosphere and for enhancing soil C sequestration (Sagrilo *et al*., 2015; Santín *et al*., 2016).

Although biochar is generally considered chemically and biologically recalcitrant, it is not completely inert and can be partially degraded by biotic and abiotic mechanisms (Kuzyakov *et al*., 2009; Santos *et al*., 2012). Published studies on biochar mineralization have indicated that biochar decomposition varies widely (e.g. from 0.22% day^{-1} (Herath *et al*., 2015) to 0.0006% day^{-1} (Whitman *et al*., 2014)). This considerable variation can be explained by several factors. The decomposition of biochar is determined mainly

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by its properties (Keith *et al.,* 2011; Luo *et al.,* 2011), soil characteristics (Santos *et al.*, 2012; Fang *et al.*, 2014a) and incubation time (Kuzyakov *et al.*, 2009; Wang *et al.*, 2015). However, the relative contributions of these factors to biochar decomposition and the relation between these controlling factors and biochar decomposition are unclear.

Research on biochar properties has suggested that production conditions and feedstock source can strongly influence biochar decomposition (Singh *et al.*, 2012; Fang *et al.*, 2014a). Higher pyrolytic temperatures usually produce more aromatic C and less labile fractions, which is likely to result in greater physicochemical recalcitrance than in biochar produced at lower temperatures (Keith *et al.*, 2011; Luo *et al.*, 2011; Fang *et al.*, 2015; Sagrilo *et al.*, 2015). Various biochar-derived feedstock materials exhibit different chemical properties that affect decomposability (Lehmann *et al.*, 2011). For example, the rate of decomposition of wood-derived biochars with a large aromatic C content is less than that of manure-derived biochars (Crombie *et al.*, 2015; Wang *et al.*, 2015). Biochar N content and C:N ratio can also be affected by different pyrolytic temperatures and feedstock type. For example, high temperatures are associated with a large C:N ratio (Luo *et al.*, 2011; Sagrilo *et al.*, 2015). However, the relations among the biochar N content, C:N ratio and biochar decomposition remain largely unexplored.

Although the effect of soil characteristics on biochar decomposition has been extensively investigated, the effect of changes in soil conditions on biochar decomposition has yet to be fully described. Cross & Sohi (2011) found that the rates of decomposition of biochar were faster in SOC-poor soil than in SOC-rich soil. However, Fang *et al.* (2015) presented the opposite results, that is, the rate of decomposition of biochar increased in soil with a large SOC content. This inconsistency is probably because the effects of SOC content on biochar decomposition cannot be distinguished from other confounding soil properties, such as N content, C:N ratio and texture (Fang *et al.*, 2014a). Therefore, the effect of SOC on biochar decomposition should be investigated further. Soil N and C:N ratio might also affect decomposition by influencing the efficiency of microbial C use (Riggs & Hobbie, 2016). Veen *et al.* (2015) reported that the decomposition of plant litter decreased as soil N content and the C:N ratio increased; however, their effect on biochar decomposition is poorly understood.

Experimental conditions, such as incubation time, incubation temperature and water content, are often considered key regulators of biochar decomposition. Wang *et al.* (2015) carried out a meta-analysis of 21 studies on biochar stability in soil and suggested that biochar decomposition decreases markedly with incubation time, which might be related to decreases in the labile biochar C fraction with prolonged incubation time. The rate of biochar decomposition increases as incubation temperature increases (Zimmermann *et al.*, 2012; Fang *et al.*, 2014b), which is probably because of increased microbial co-metabolism with increasing incubation temperature (Fang *et al.*, 2015). Nguyen & Lehmann (2009) observed that biochar degradation was significantly larger under unsaturated and alternating saturated–unsaturated conditions than under constant saturation. Nevertheless, the relation between biochar decomposition and water content remains unclear. Therefore, our understanding of its decomposition in soils with different water contents needs to be improved. Biochar decomposition can also be affected by the addition of nutrients, such as glucose, nitrogen or plant residues. They have been reported to increase (Hamer *et al.*, 2004; Kuzyakov *et al.*, 2009), decrease (Liang *et al.,* 2010) or have no effect on its decomposition (Santos *et al.,* 2012; Maestrini *et al.*, 2014). Apparently, the direction and extent of the effects of nutrient addition appear difficult to predict.

Most individual studies have been carried out under various incubation conditions and have used a limited number of types of soil and biochar (Sagrilo *et al.,* 2015). Therefore, researchers find it difficult to present robust conclusions on the nature of changes in biochar decomposition within a wide range of biochar properties, soil characteristics and incubation conditions. Consequently, the effects of these factors on its rates of decomposition require comprehensive analysis so that individual contributions of these factors can be determined.

A boosted regression tree (BRT) is a powerful method of modelling that combines the strengths of regression trees and boosting algorithms (Elith *et al.*, 2008; Zhang *et al.*, 2015). Compared with a conventional regression model, the BRT model has several advantages that make it useful for evaluating the relation between predictors and ecological progress (Jorda *et al.*, 2015; Zhang *et al.*, 2015). First, BRTs can handle different types of predictor variables and missing data in predictors. Second, BRTs can fit complex nonlinear relations and handle the interactions of predictors by the hierarchical structure of a tree. Third, data transformation or elimination of outliers is not required in BRTs, and the relative importance of each predictor to the model can also be estimated. Ecologists have used BRT models to elucidate the variation in other ecological processes. For example, our previous work demonstrated that the BRT model accounted for 32.3% of the variation in the effect of soil fauna on plant litter decomposition (Zhang *et al.*, 2015). Jorda *et al.* (2015) developed a BRT model that explained 36 and 15% of the variation in near-saturated hydraulic and saturated hydraulic conductivity, respectively.

This study evaluates the effects of biochar properties, soil characteristics and incubation conditions on biochar decomposition. It also describes the quantitative relation between rates of biochar decomposition and these factors, and the relative importance of biochar properties, soil characteristics and incubation conditions.

Materials and methods

Data collection

We carried out a systematic search of the Web of Science and Google Scholar databases to identify biochar decomposition data in the literature. The search terms were ‘biochar’, ‘black carbon’, ‘pyrogenic carbon’, ‘PyOM’, ‘char’ and ‘charcoal’. A total of 812 observations taken from 23 studies were selected (S1). The selection criteria were as follows: (i) biochar decomposition should be studied by isotopic techniques (^{13}C- or ^{14}C-labelling) to separate

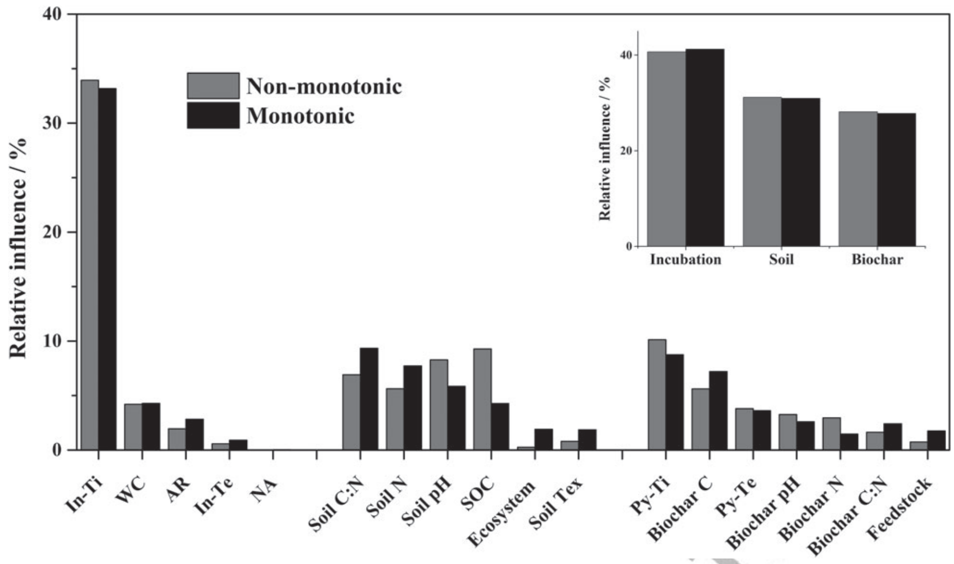

Figure 1 Boosted regression tree (BRT) model indicating the relative contribution (%) of variables to the rate of biochar decomposition. Black and grey bars show data from the BRT model with and without monotonic constraints. Variables are as follows: In-Ti, incubation time; WC, water content; AR, addition rate; In-Te, incubation temperature; NA, nutrient addition; Soil C:N; SOC, soil organic carbon; soil pH; soil N; ecosystem, ecosystem type; soil tex, soil texture; Py-Ti, pyrolysis time; biochar C; Py-Te, pyrolysis temperature; biochar N; biochar C:N; feedstock.

biochar-derived CO_2 and CO_2 derived from other C sources (e.g. native soil organic matter or plant residues) and (ii) at least one of the selected explanatory variables was determined. The digitizer in OriginPro 9.0 was used to extract data points from figures in these published studies.

We used a BRT model with three latent variables, that is, biochar properties, soil characteristics and incubation conditions, to determine their effects on the rates of biochar decomposition. The latent variables were reflected by selected variables (i.e. indicators). Biochar properties, including pyrolysis time and temperature, biochar C and N contents, C:N ratio, pH and feedstock, were selected as potential indicators. For soil characteristics, we selected six indicators: soil C and N contents, C:N ratio, pH, ecosystem type and soil texture. For incubation conditions, we selected five indicators: incubation time, temperature and water content, rates of biochar and nutrient addition.

Data analysis

The data for decomposition dynamics of biochar were reported as emitted CO_2-C derived from biochar (mg C g^{-1} biochar-C) or biochar mineralization (% of addition) in most of the studies; therefore, we recalculated the rates of biochar decomposition and represented them as percent per day (% day^{-1}).

The BRT models were implemented with the packages gbm and dismo in the statistical software R (version 2.15.2; R Development Core Team, 2009) (Elith *et al.*, 2008). In the BRT analysis, we chose Gaussian as the error structure for the loss function because of the characteristics of our response variable (Zhang *et al.*, 2015). Model performance was also controlled by learning rate, tree complexity, bagging fraction and cross-validation (De'ath, 2007; Elith *et al.*, 2008; Soykan *et al.*, 2014). Learning rate determined the contribution of each tree to the growing model. Tree complexity refers to the number of nodes in a tree and controlled the level of interactions in BRT. Bagging fraction set the proportion of data used for model building at each step. Cross-validation specified the number of times that the data should be divided randomly for model fitting and validation. To select the optimum model, the parameter setting was based on the empirical rules recommended for BRT modelling. Twenty-seven models were fitted with the following parameter settings: learning rates of 0.01, 0.005 and 0.001, bag fractions of 0.6, 0.5 and 0.4, ten-, eight- and five-fold cross-validations and a tree complexity of 4 to account for potentially large numbers of interactions between predictor variables. By trial-and-error we found that the best BRT model had a cross-validation deviance (predictive deviance) of 0.011 (± one standard error = 0.002) from a learning rate of 0.01, bag fraction of 0.6 and five-fold cross-validation. To reduce the risk of over-fitting, we also applied monotonic constraints to biochar properties, soil characteristics and incubation conditions, resulting in a refitted model with a cross-validation deviance of 0.015 (± one standard error = 0.002). The results are similar (Figures 1–4); therefore, we interpreted the model with monotonic constraints. Moreover, we also assessed the extent of interaction effects between predictors. However, the strength of the effect for each possible pair of predictors was weaker (Table 1). Details of the interaction effects between predictors are provided in Table 1 and Figures S1–S4 in File S1.

Boosted regression trees can provide the relative effect of the predictor variables in the model (Friedman, 2001). The relative effect of each predictor is based on the number of times a variable is used in the model for splitting, weighted by the squared improvement to the model as a result of each split, and averaged

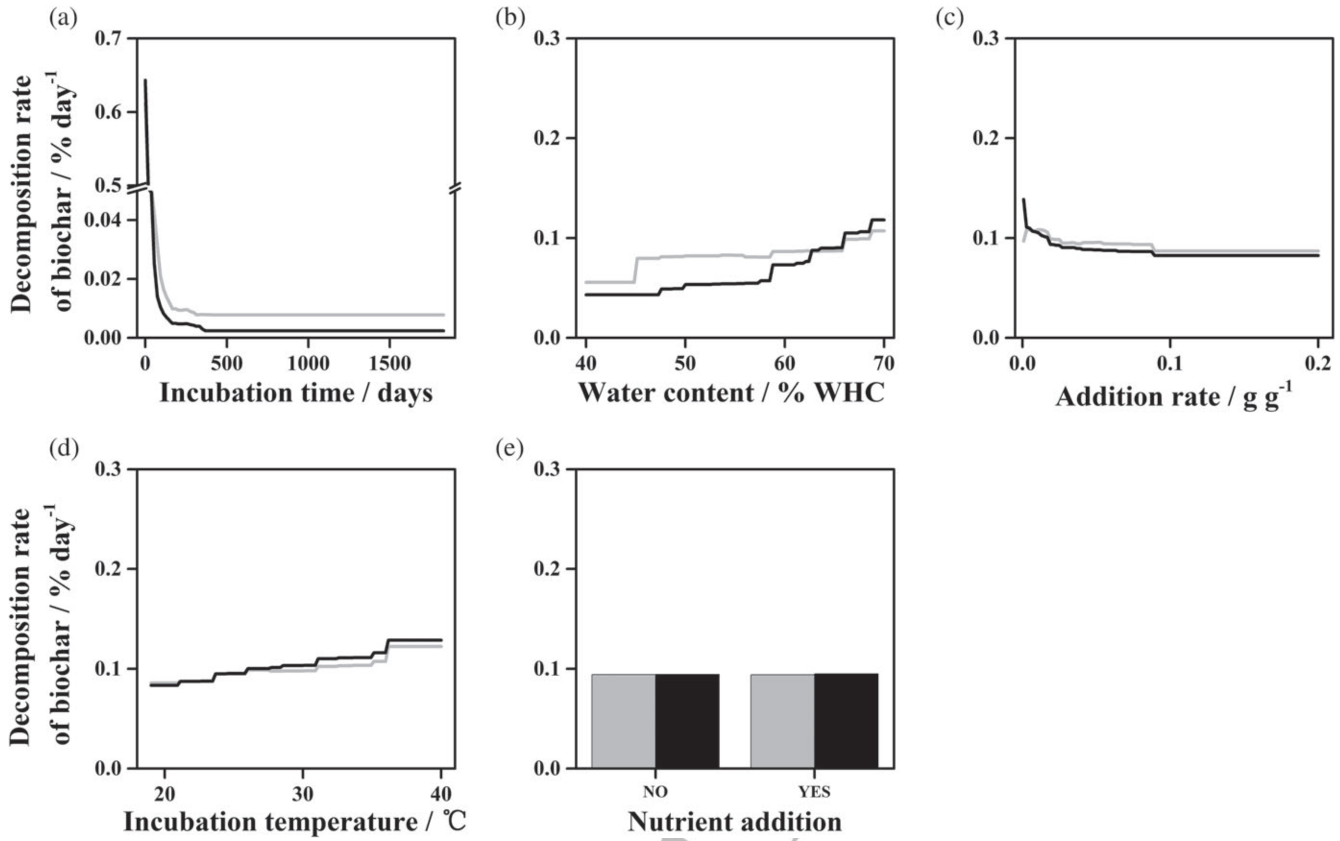

Figure 2 Partial dependence plots showing the effect of the changes in incubation conditions on the rate of biochar decomposition by considering the following variables used in the boosted regression tree (BRT) model: (a) incubation time, (b) water content, (c) addition rate, (d) incubation temperature and (e) nutrient addition. The fitted functions reveal the relations between the rate of biochar decomposition and each variable. The responses of the rate of biochar decomposition to monotonic constraints are shown in black and those without the constraints are shown in grey.

over the entire model (Soykan *et al.*, 2014; Zhang *et al.,* 2015). To interpret the fitted functions better, we calculated the relative effect of all predictor variables to quantify the contribution of predictors to the rate of biochar decomposition. Then, the relative effect of each variable was scaled such that the sum adds to 100. Variables with a larger percentage corresponded to a stronger relative effect on the decomposition rate of biochar.

Results

Overall, the mean rate of biochar decomposition was 0.011% day^{-1} (95% confidence interval (CI) = −0.0018 to 0.0239%). The BRT model accounted for 95% of the variation in the rate of decomposition. Incubation conditions, soil characteristics and biochar properties accounted for 41, 31 and 28% of that variation, respectively (Figure 1 inset).

Effect of incubation conditions

Water content, rate of addition of biochar, incubation time and temperature, and nutrient addition affected biochar decomposition by 4, 3, 33, 1 and 0%, respectively (Figure 1).

The rate of decomposition decreased markedly with prolonged incubation time (Figure 2a). The average rates of decomposition rapidly decreased from 0.6433 to 0.0024% day^{-1} within 1 year, and then remained at a low rate. As incubation temperature and water content increased, the rate of decomposition increased (Figure 2b,d). Analysis with the BRT model revealed that the rate of decomposition was negatively related to that of biochar addition. The rate of decomposition decreased slowly and then became constant at rates of biochar addition >0.089 g g^{-1} (Figure 2c). However, the addition of nutrients did not affect the rate of biochar decomposition (Figure 2e).

Effect of soil characteristics

The C:N ratio, N content, pH, soil C, ecosystem type and soil texture affected the decomposition of biochar in the following proportions: 9, 8, 6, 4, 2 and 2%, respectively (Figure 1).

Biochar decomposition decreased considerably with increasing C:N ratio up to 9; at C:N ratios >9 there was little difference in the rate of decomposition (Figure 3a). The rate also decreased as soil N content increased (Figure 3b). In contrast, the rate increased as SOC content increased (Figure 3d) and also increased markedly

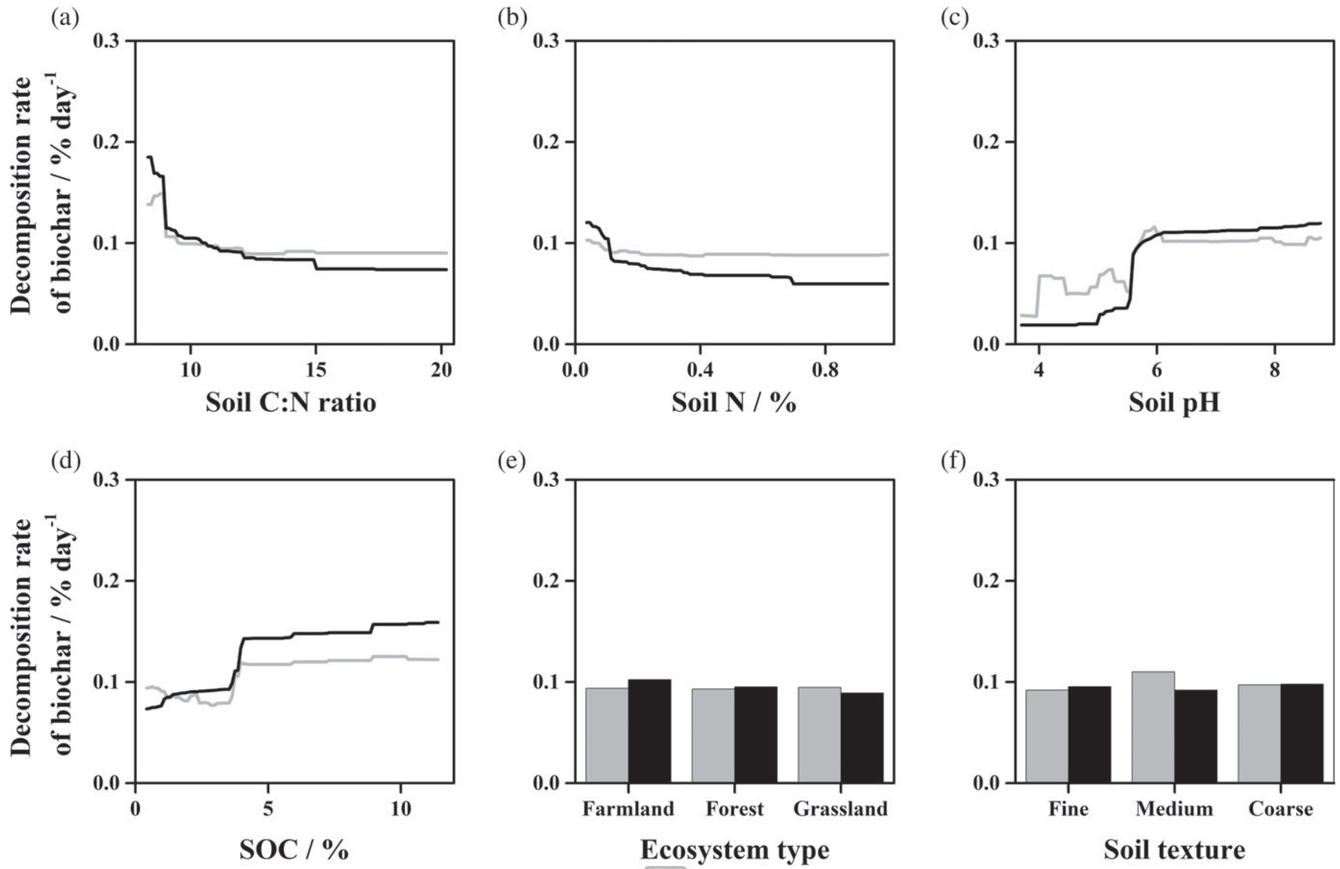

Figure 3 Partial dependence plots illustrating the effect of soil characteristics on the rate of decomposition of biochar using each variable in the boosted regression tree (BRT) model: (a) soil C:N ratio, (b) soil N content, (c) soil pH, (d) soil organic carbon (SOC) content, (e) ecosystem type and (f) soil texture. The responses of the rate of biochar decomposition to monotonic constraints on these are shown in black and those without constraints are shown in grey.

with increasing pH from 5 (0.029% day^{-1}) to 6 (0.108% day^{-1}) and was relatively stable at pH higher than 6 (Figure 3c). Ecosystem and soil texture had no effect on the rate of biochar decomposition (Figure 3e,f).

Effect of biochar properties

Pyrolysis time, biochar C content, pyrolysis temperature, pH, C:N ratio, N content and feedstock source affected biochar decomposition by relatively small amounts: 9, 7, 4, 3, 2, 1 and 2%, respectively (Figure 1).

The rate of decomposition of biochar markedly decreased with pyrolysis time and then became constant when pyrolysis time exceeded 2 h (Figure 4a). Similarly, the rate of decomposition decreased (seemingly stepwise) with increasing temperature up to 600°C and thereafter was relatively stable (Figure 4c). The rates of decomposition were negatively correlated with biochar C and N contents, and its pH (Figure 4b,d,f). The rate of decomposition increased with increasing C:N ratio up to 40 and was relatively stable above that (Figure 4e). The feedstock used for biochar production appeared to have little effect on its rate of decomposition (Figure 4g).

Discussion

To our knowledge, this study is the first to use a BRT model to quantify the relative contributions of incubation conditions, soil characteristics and biochar properties to the rates of decomposition of biochar. Our results show that such a model presently accounts for 95% of the variation in biochar decomposition. The proportion of variation accounted for by the BRT model applied to biochar decomposition exceeds that reported by Zhang *et al.* (2015) and Jorda *et al.* (2015) for other ecosystem processes. This result indicates that, after many years of research, our current knowledge of the factors that control the complex nature of biochar decomposition is considerable.

Effects of incubation conditions on the decomposition rate of biochar

Our finding that incubation time was the most important predictor of biochar decomposition (contributing 33% to the rate) is consistent with that described by Wang *et al.* (2015), who found that incubation time was a relevant factor that affected rates of biochar degradation in soil. The sharp decrease in rate of decomposition of biochar within 1 year (Figure 2a) indicates that biochar contains an easily

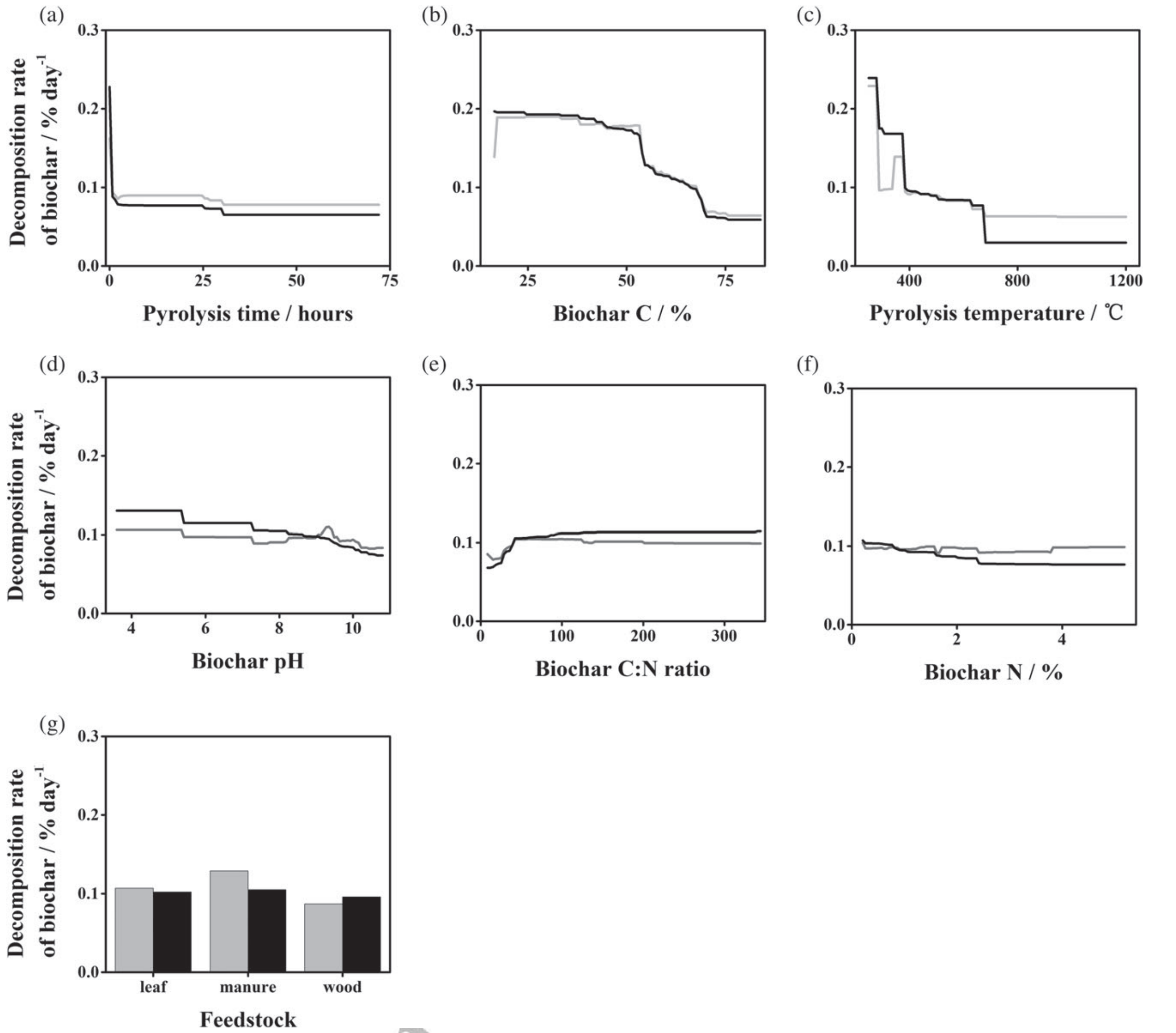

Figure 4 Partial dependence plots describing the effect of biochar properties on the rate of biochar decomposition using each variable in the boosted regression tree (BRT) model: (a) pyrolysis time, (b) biochar C content, (c) pyrolysis temperature, (d) biochar pH, (e) biochar N content, (f) biochar C:N ratio and (g) feedstock. The responses of biochar decomposition rate to monotonic constraints on these properties are shown in black and those without constraints are shown in grey.

decomposable component and that the rate of biochar decomposition stabilizes after this readily available C is exhausted (Crombie *et al.*, 2015; Sagrilo *et al.*, 2015). Although only 16% of the data used here represented incubation times >1 year, our analysis shows that rates of biochar decomposition appeared stable after 1 year. Other incubation studies, such as the decomposition of plant litter, lasted >1 year, which was a much shorter time period than those on biochar decomposition. This observation suggests that researchers have exerted considerable efforts to explore biochar decomposition (Bird *et al.*, 2015; Santín *et al.*, 2016).

Rates of biochar decomposition are faster in mild and wet conditions than in cold or dry environments (Nguyen & Lehmann, 2009; Fang *et al.*, 2014b), which is similar to rates of decomposition of plant litter. In contrast to the decay of litter, our results indicate that temperature appeared to play a minor role in biochar decomposition. According to enzyme kinetic theory, chemically recalcitrant C (e.g. biochar) requires greater activation energy for decomposition and is therefore more sensitive to temperature (Q_{10}) than labile C (e.g. plant litter) (Davidson & Janssens, 2006; Nguyen *et al.*, 2010). Previous research has reported that the Q_{10} values of plant litter and soil organic matter were approximately 3 and 2, respectively (Hyvönen *et al.*, 2005; Salinas *et al.*, 2011). However, our results showed that rates of biochar decomposition were estimated to increase by about 43% for about a 20°C rise in temperature (the

Table 1 A ranked list of the extent of the interaction effects between predictors

Rank	Variable 1 (index)	Variable 1 (names)	Variable 2 (index)	Variable 2 (names)	Interaction effects
1	6	Biochar C	1	Incubation time	0.75
2	18	Pyrolysis time	1	Incubation time	0.18
3	10	Soil organic carbon	1	Incubation time	0.14
4	16	Feedstock	1	Incubation time	0.11
5	5	Addition rate	1	Incubation time	0.10
6	15	Ecosystem type	13	Soil pH	0.06
7	13	Soil pH	1	Incubation time	0.05
8	12	Soil C:N	1	Incubation time	0.05
9	17	Pyrolysis temperature	13	Soil pH	0.04
10	11	Soil N	3	Water content	0.04
11	13	Soil pH	10	Soil organic carbon	0.03
12	17	Pyrolysis temperature	1	Incubation time	0.02
13	13	Soil pH	3	Water content	0.02
14	10	Soil organic carbon	3	Water content	0.02
15	9	Biochar pH	1	Incubation time	0.02
16	8	Biochar C:N	6	Biochar C	0.02

incubation temperature range from 19°C to 40°C included in this study), rather than the similar four-fold increase expected, according to the Q_{10} value of soil organic matter. This indicated that rates of biochar decomposition were much less sensitive than those of plant litter or soil organic matter in response to incubation temperature. Fang *et al.* (2014b) also reported that biochar decomposition is less sensitive to changes in incubation temperature than is native carbon. The marked difference in temperature sensitivity between biochar and plant litter indicates that mechanisms controlling its temperature sensitivity may be different and require further research.

According to stoichiometric theory, nutrients in litter, such as N and P contents, are generally the main limiting factors of decomposition (Manzoni *et al.*, 2010). The addition of N can stimulate the decomposition of plant litter, especially poor-quality litter, such as pine needles, by modifying its C:N ratio (Sterner & Elser, 2002). However, the negligible effect of nutrient addition on biochar decomposition in this study suggests that biochar decomposition might primarily be limited by readily available C rather than nutrients.

Effects of soil characteristics on the rate of biochar decomposition

The physicochemical characteristics of soil play important roles in determining rates of biochar decomposition. Overall, the rate is larger in soil with large SOC contents and small C:N ratios than in soil with small SOC contents and large C:N ratios. In contrast to previous findings (Cross & Sohi, 2011; Sagrilo *et al.*, 2015), our results demonstrated that soil with large SOC contents had enhanced biochar decomposition. This inconsistency might be attributed to the following reasons. First, soil with large SOC contents and small C:N ratios might support more biomass and microbial activity than soil with small SOC contents and large C:N ratios (Keith *et al.*, 2011; Fang *et al.*, 2014a). Second, biochar decomposition did not respond to the addition of nutrients, which suggests that readily available C might be a limiting factor in biochar decomposition. Thus, soil with larger SOC content might compensate for the C-limiting effects. Third, individual studies have used few soil types. Therefore, establishing a reliable relation between biochar decomposition and SOC is difficult. Soil N content had only a weak effect on the rate of decomposition of biochar, probably because biochar decomposition was not limited by nutrients (Figure 2e).

Effects of biochar properties on its rate of decomposition

The seven biochar properties incorporated in our BRT model accounted for 28% of the variation in decomposition, indicating that these properties are almost as significant as those of the accompanying soil.

We anticipated that feedstock source would markedly affect the properties of biochar and consequently influence its decomposition. However, our results showed that feedstock only slightly affected the rates of biochar decomposition, although the physical state and properties of biochar might vary considerably for different feedstock types, such as leaf, wood and manure-derived biochar. This phenomenon might result from the conditions under which the biochar was produced, which have important effects in determining biochar properties (Lehmann *et al.*, 2011; Crombie *et al.*, 2015). In general, the concentration of C in plant residues is less than 50% (Hättenschwiler *et al.*, 2008); however, the C content markedly increases from pyrolytic processes, the aromatic C content increases concomitantly and relative recalcitrance against microbial decomposition occurs as a consequence (Luo *et al.*, 2011; Fang *et al.*, 2015).

The slight effects of biochar N concentration and C:N ratio on its decomposition are in contrast with litter decomposition, where these factors usually have a strong influence (Zhang *et al.*, 2008). The decomposition of plant litter is often positively correlated with N content and inversely related to the C:N ratio (Zhang *et al.*, 2008). However, much of the N within biochar is unavailable to soil microorganisms (Biederman & Harpole, 2013) and biochar decomposition might be inhibited by a large proportion of aromatic C and the degree of aromatic condensation rather than by biochar N or C:N ratio. Previous studies have also suggested that aromatic alkene-C structures play important roles in influencing biochar decomposition (Santos *et al.*, 2012; Fang *et al.*, 2015), and the degree of aromaticity increases with temperature and the duration of pyrolysis (Luo *et al.*, 2011; Maestrini *et al.*, 2014). Thus, further research is required to determine the importance of the degree of aromaticity in biochar decomposition.

Conclusions

This study enabled us to determine the relative contributions of incubation conditions, soil characteristics and biochar properties on the rate of biochar decomposition. Our BRT model accounted for 95% of the variation in biochar decomposition. Incubation time was the strongest controlling factor in the rate of biochar decomposition, and although soil characteristics and biochar properties accounted for less of the variation, they were significant and almost equal in determining the decomposition.

Supporting Information

The following supporting information is available in the online version of this article:

File S1. Supporting information file.

Supplementary references. List of references for the 23 published studies used in the current BRT analysis.

Table S1. A ranked list of the extent of the interaction effects between predictors.

Figure S1. Three-dimensional partial dependence plots showing the interaction effect of incubation time and biochar C content on the rate of biochar decomposition.

Figure S2. Three-dimensional partial dependence plots indicating the interaction effect of incubation time and pyrolysis time on the rate of biochar decomposition.

Figure S3. Three-dimensional partial dependence plots illustrating the interaction effect of incubation time and SOC on the rate of biochar decomposition.

Figure S4. Three-dimensional partial dependence plots illustrating the interaction effect of incubation time and rate of addition of biochar on that of its decomposition.

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