

Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data

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Received: 24 January 2013 / Accepted: 5 June 2013 / Published online: 6 July 2013
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Abstract

Background and aims For the last decade, there has been an increasing global interest in using biochar to mitigate climate change by storing carbon in soil. However, there is a lack of detailed knowledge on the impact of biochar on the crop productivity in different agricultural systems. The objective of this study was to quantify the effect of biochar soil amendment (BSA) on crop productivity and to analyze the dependence of responses on experimental conditions. **Methods** A weighted meta-analysis was conducted based on data from 103 studies published up to April, 2013. The

effect of BSA on crop productivity was quantified by characterizing experimental conditions.

Results In the published experiments, with biochar amendment rates generally $<30 \text{ t ha}^{-1}$, BSA increased crop productivity by 11.0 % on average, while the responses varied with experimental conditions. Greater responses were found in pot experiments than in field, in acid than in neutral soils, in sandy textured than in loam and silt soils. Crop response in field experiments was greater for dry land crops (10.6 % on average) than for paddy rice (5.6 % on average). This result, associated with the higher response in acid and sandy textured soils,

Responsible Editor: Hans Lambers.

Electronic supplementary material The online version of this article (doi:10.1007/s11104-013-1806-x) contains supplementary material, which is available to authorized users.

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suggests both a liming and an aggregating/moistening effect of BSA.

Conclusions The analysis suggests a promising role for BSA in improving crop productivity especially for dry land crops, and in acid, poor-structured soils though there was wide variation with soil, crop and biochar properties. Long-term field studies are needed to elucidate the persistence of BSA's effect and the mechanisms for improving crop production in a wide range of agricultural conditions. At current prices and C-trading schemes, however, BSA would not be cost-effective unless persistent soil improvement and crop response can be demonstrated.

Keywords C-sequestration · Soil fertility · Soil amendment · Meta-analysis · Soil carbon

Abbreviations

BSA Biochar soil amendment

RC Relative change over control

Introduction

Soil organic carbon (SOC) is known to play an important role in maintaining soil fertility and crop productivity (Díaz-Zorita et al. 2002; Lal 2004; Pan et al. 2009). Enhancing SOC stocks in croplands with good management practices could also significantly contribute to climate change mitigation in agriculture (Smith et al. 2007, 2008). Direct incorporation of crop residues as well as organic manure to soils has been traditionally performed to maintain soil resilience and carbon (C) stocks. However, the residence time of these C sources in soil is relatively short because of mineralization, perhaps less than 30 years (Lehmann et al. 2006). Moreover, such an incorporation of fresh organic matter would potentially lead to an increase in the production of methane (CH₄) in rice paddies (Yan et al. 2005; Shang et al. 2011).

In contrast, C from biochar could be stabilized in soil for long periods, potentially hundreds of years (Lehmann et al. 2006; Kleber 2010; Schmidt et al. 2011; Woolf and Lehmann 2012). Furthermore, biochar soil amendment (BSA) has been shown to effectively reduce nitrogen (N) fertilizer-induced nitrous oxide (N₂O) emissions from agricultural soils (Yanai et al. 2007; Liu et al. 2012; Zhang et al. 2010) with no or minimal increase in CO₂ and CH₄

emissions (Spokas and Reicosky 2009; Karhu et al. 2011; Zhang et al. 2012a, b, c). Thus, biochar, produced via pyrolysis of biomass, has been recommended as an option to enhance SOC sequestration and mitigate greenhouse gas (GHG) emissions with the co-benefits of improving soil productivity and ecosystem functioning in world agriculture (Lehmann et al. 2006; Sohi 2012; Sohi et al. 2010; Woolf et al. 2010).

Given the low price for C sequestered, the application of biochar must demonstrate significant long term yield improvements. The income received from additional crop yield must be greater than the biochar cost of the biochar, whether produced or bought. While benefits for crop yields have often been documented in the literature (Glaser et al. 2002; Jeffery et al. 2011; Spokas et al. 2012; Biederman and Harpole 2013), overall assessments of crop productivity effects are difficult due to the wide variation of experimental conditions including soil type and environment, crop species and biochar properties and application rate. In a meta-analysis of data from 16 publications available up to March 2010, Jeffery et al. (2011) gave a general estimation of 10 % crop productivity increase with BSA. However, the number of reported biochar experiments has increased rapidly since 2010 worldwide. More recently, Biederman and Harpole (2013) also reported significant increase of aboveground biomass and crop yield with BSA. This study updated the early work of Jeffery et al. (2011). The specific objectives of this work was to examine the effect and extent of BSA on crop productivity across a wide range of conditions and to evaluate variation in crop response with different experimental conditions of soil, crop, and biochar types. We aimed to draw robust conclusions to assist in rational biochar application in crop production systems and highlight future research priorities in biochar science and technology in agriculture.

Materials and methods

Data sources

Data were compiled from the literature reporting either field and/or pot studies that compared crop yields and/or aboveground biomass production between treatments with and without BSA treatment. We searched the literature published up to April, 2013 via electronic

databases including Springer Link, Wiley-Blackwell, Web of Science, and the Chinese magazine network (CNKI). In the case of crop responses presented only in the figures, Grafula 3 software was used to extract numerical data. Overall, 103 publications and 880 pairs of data were obtained to form a database (Supporting Table 1 in the [Electronic supplementary material](#)). As a comparison, there were 87 more studies and 703 more pairs of data in this study than in the review reported by Jeffery et al. (2011).

In the published studies, a variety of parameters were used to describe crop yield or aboveground biomass (hereafter termed “biomass”) production under BSA. Here, crop productivity referred to either crop yield or biomass or both as recorded in the literature cited. Soil properties before BSA experiment and characteristics of biochar used for BSA as reported in the studies were used to analyze the factors influencing crop growth responses to BSA. Soil properties included topsoil organic C and N concentrations, soil pH, cation exchange capacity (CEC), and texture, while biochar parameters included concentrations of organic C and N, pH, feedstock source, and pyrolysis temperature. In most studies, crop type, duration of the experiment, as well as N fertilization and biochar application rates were also described and addressed here in the assessment.

Meta-analysis

A meta-analysis was conducted to characterize the response of crop productivity to biochar by comparing the treatments with and without BSA. Following Hedges et al. (1999) and Johnson and Curtis (2001), an effect size was calculated as a natural log value of the response ratio:

$$r = X_T/X_C \quad (1)$$

Where, X_T and X_C was the mean crop productivity value under a BSA treatment and the control (without BSA) of a single experiment. Moreover, standard deviation and the number of replicates were used as a measure of variance. The weight for each effect size was considered as its inverse variance. In addition, enquiries were made to the corresponding authors prior to this analysis for obtain missing standard deviation data in very limited studies. A standard deviation of 10.12 % was assigned to a mean before calculating effect size following a modified methodology by Luo

et al. (2006), if data were not available. Here, this figure is the mean percentage of the reported standard deviations of all means in the entire database. A random effect model was used in this meta-analysis. For the field studies with more than 1 year of crop yield or biomass data, a single mean and standard deviation was calculated from individual means (the mean of each year) before calculating the effect size.

In order to determine the key factors affecting the response of crop productivity to BSA, the experiments were grouped according to experimental design in terms of experiment type (field or pot), yield or biomass, cropping system (paddy rice vs. dry land crops), crop variety, N fertilization rate, duration of field experiment, biochar properties including pyrolysis temperature, pH and the feedstock, and to soil conditions in terms of texture, pH, CEC and C/N status. It should be noted that groups with fewer than three studies were excluded from each analysis.

Data processing and statistics

Data treatment and processing was performed in Microsoft Excel 2010, and calculations with meta-analysis were conducted in natural log of response ratios following the procedure given by Hedges et al. (1999). However, we converted the natural log transformed ratios to the relative percent changes (RC) when presenting and interpreting the results. All figures were expressed as the mean RC and 95 % confidence intervals (CIs) for each group. Means were considered significantly different from zero if the 95 % CIs did not overlap zero and were considered to be significantly different from one another if their 95 % CIs were non-overlapping.

Results

General trends of biochar experiments

Figure 1 shows an overview of the geographical spread of the studies used in this analysis. The database included 59 pot experiments from 21 countries and 57 field experiments from 21 countries across all continents except for Antarctica. Figure 2 shows the frequency distribution of all the studies ranked according to the year of publication and to the location (continent) of the research organizations. Nearly 81 %

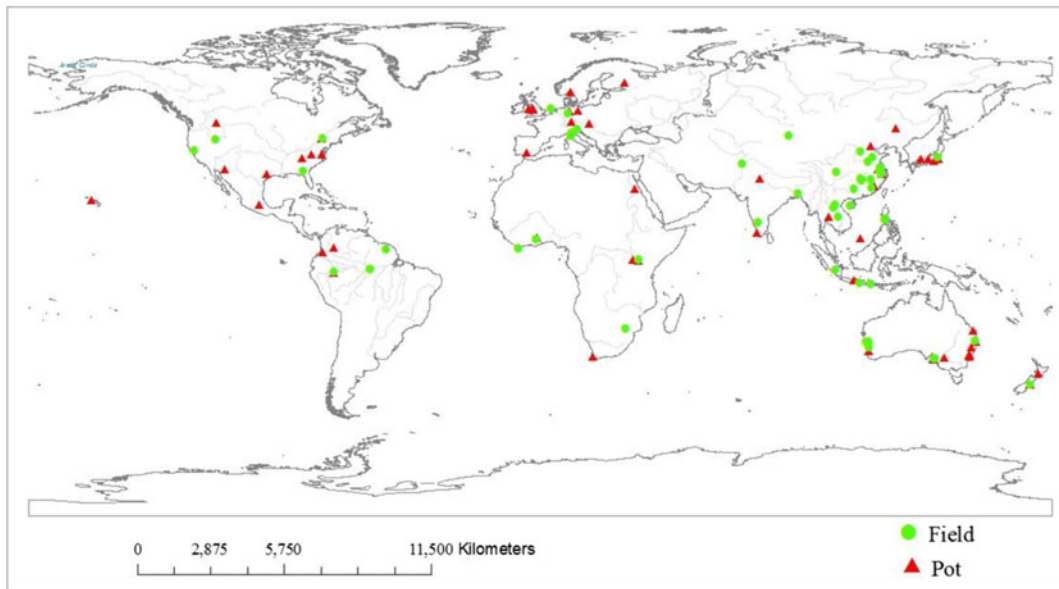


Fig. 1 Site location of experiments used in this study

of the experiments in this meta-analysis were published in the year of 2010–2013. Most studies were conducted using rates $<30 \text{ t ha}^{-1}$, but rates ranged from 0.5 to 240 t ha^{-1} (Fig. 3). Of the 370 paired data of field experiments, 152 were from experiments conducted over 1 year.

Response of crop productivity to BSA: variation with experimental conditions

Figure 4 shows the responses of crop productivity to BSA in terms of experimental design. Crop yields were more frequently reported than biomass yields in field studies, but the reverse was true in pot studies. On average, BSA increased crop productivity by 11.0 % over the control. BSA resulted in higher increases in

crop biomass (12.5 % on average) than in crop yield (8.4 % on average), but a smaller positive crop productivity response was observed in field (9.1 % on average) than in pot experiments (11.1 % on average) though in the pot experiments crop yield increase was not statistically higher than zero (Fig. 4). The increase in crop productivity was much smaller for paddy rice (5.6 % on average) than for dry land crops (10.6 % on average) (Fig. 4). For the studies measuring both (crop yield and biomass), no difference in response to BSA between of crop yield and of biomass was observed. Overall, few studies (9.8 % of the data pairs) reported negative crop responses and these were generally restricted to specific biochar types (see below).

Figure 5 presents the crop productivity response to BSA in field studies in terms of the persistence of effects

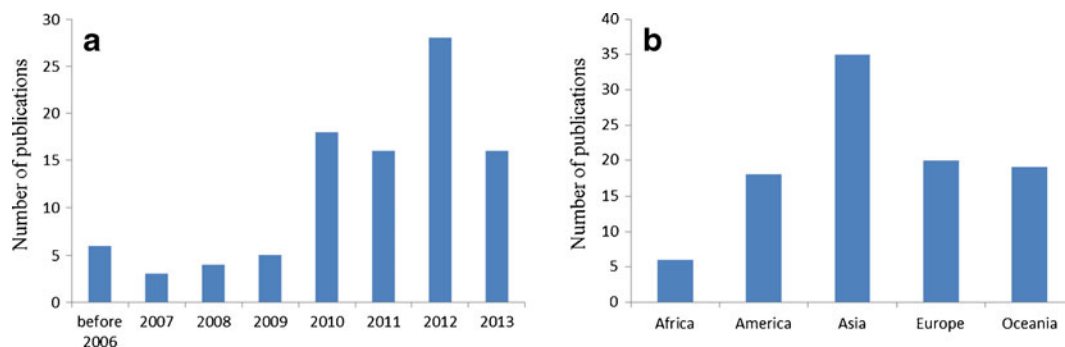


Fig. 2 Distribution of publications in time sequence (a) and continent level (b)

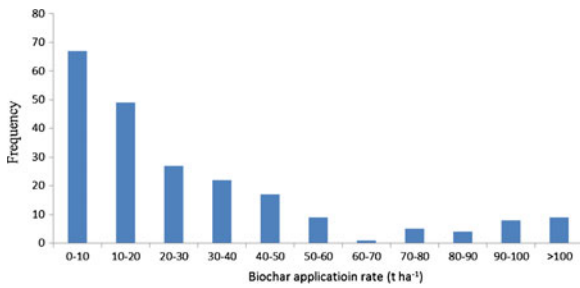


Fig. 3 Frequency distribution of biochar application rate (in tons per hectare)

in experiments of different duration. Generally, greater responses were observed in experiments sustained over several years than in those conducted for a shorter period. Compared with control, there was a significant crop productivity increase in years 1 and 2 but not in 3 and 4 (Fig. 5).

Crop productivity responses to BSA also varied with crop type (Fig. 6). Generally, greater positive responses were found in experiments with legumes, vegetables and grasses. The average increase in crop productivity was 30.3, 28.6, and 13.9 % respectively for legume crops, vegetables, and grasses and 8.4, 11.3, and 6.6 %

Fig. 4 Response of crop productivity to biochar additions expressed as the average percentage changes from control with 95 % confidence intervals for **a** all field and pot studies combined, **b** categories of experimental types (field vs. pot), **c** categories of harvest part (yield vs. aboveground biomass), **d** the interaction of experimental types and harvest part, **e** categories of harvest part for studies reported both yield and aboveground biomass, and **f** categories of cropping systems in field studies only. The figures in brackets represent the numbers of data pairs

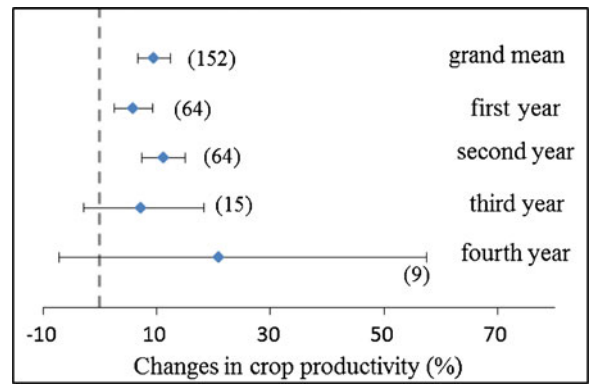


Fig. 5 The effect of experiment duration on crop productivity expressed as the average percentage changes from control with 95 % confidence intervals. The figures in brackets represent the numbers of data pairs

respectively for maize, wheat, and rice. Yield increases with BSA were greater than biomass increases for maize, whereas, the reverse was true for wheat.

Figure 7 shows crop productivity responses to BSA in relation to N application rate. Overall, smaller crop productivity increases were observed at higher (>150 kg ha⁻¹) N fertilizer application rates in all experiments (Fig. 7b). However, the addition of N

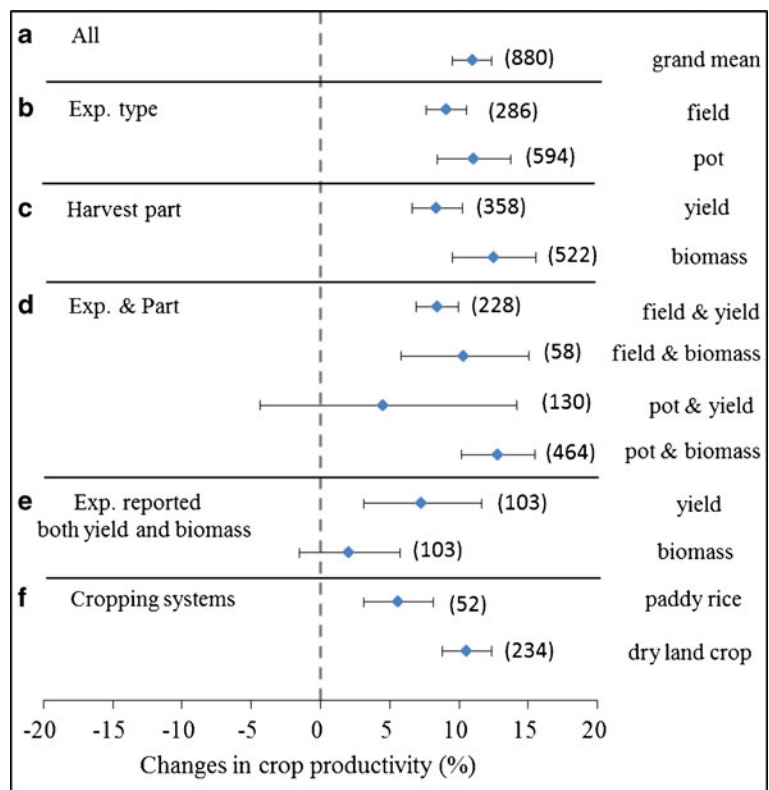
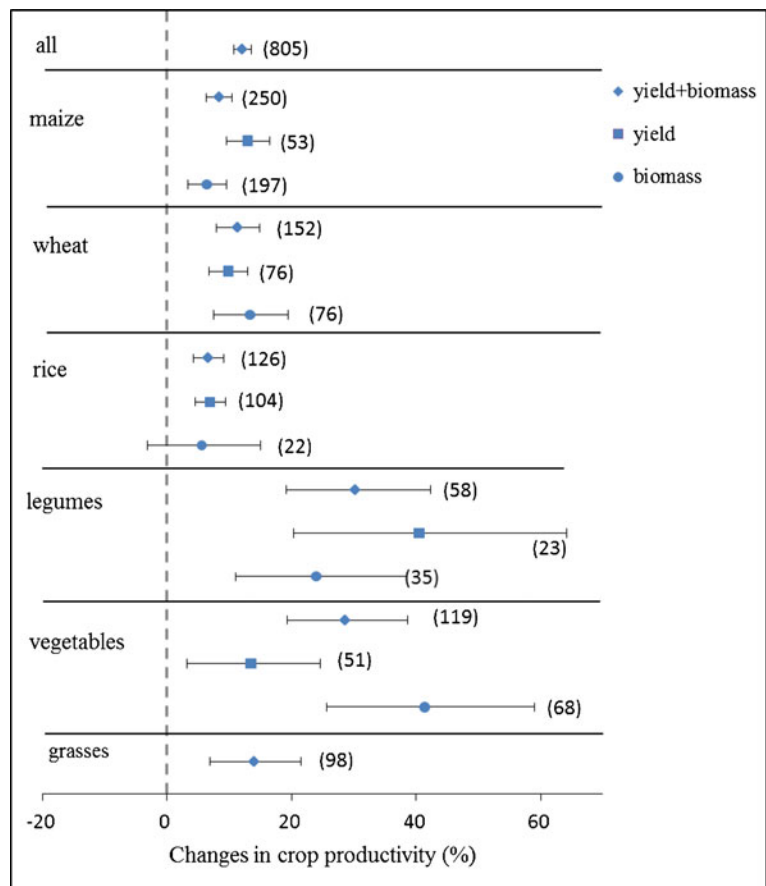


Fig. 6 Crop productivity response of different crop species to biochar amendment expressed as the average percentage changes from control with 95 % confidence intervals. The figures in brackets represent the numbers of data pairs



fertilizer did not affect crop response to BSA within field or pot experiments.

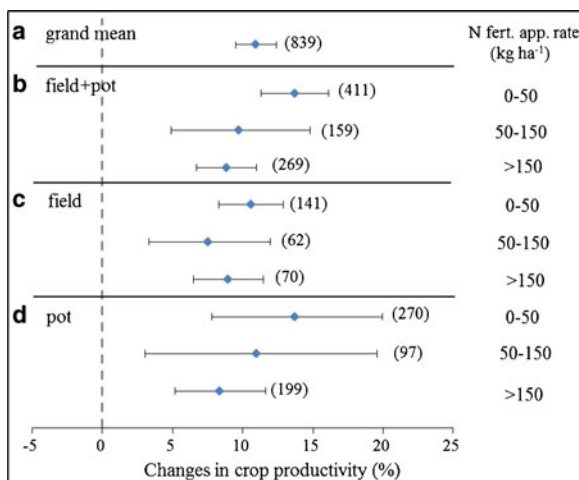


Fig. 7 The effect of N fertilization on crop productivity response to biochar amendment expressed as the average percentage changes from control with 95 % confidence intervals. The figures in brackets represent the numbers of data pairs

Variation of crop responses with soil condition

Figure 8 shows the effects of BSA on crop productivity in relation to soil properties. BSA increased crop productivity by 29.5, 16.0, 6.8, and 6.7 %, respectively, for sand, clay, silt, and loam soil. Clearly, a much higher crop productivity increase was obtained in sandy soils. The increase in crop productivity was also greater (30.2 %) in acid soils (pH<5.0) than in neutral soils. However, no positive response was observed in neutral soils. Crop productivity response to BSA showed no general trends with either SOC or N concentrations (data not shown). Nevertheless, greater crop productivity increases were observed in soils with low C/N ratio (<9.0) rather than in those with medium or high C/N ratios.

Effect of biochar properties on crop response to BSA

The feedstock type, pyrolyzing temperature, biochar pH and amendment rate all influenced the direction

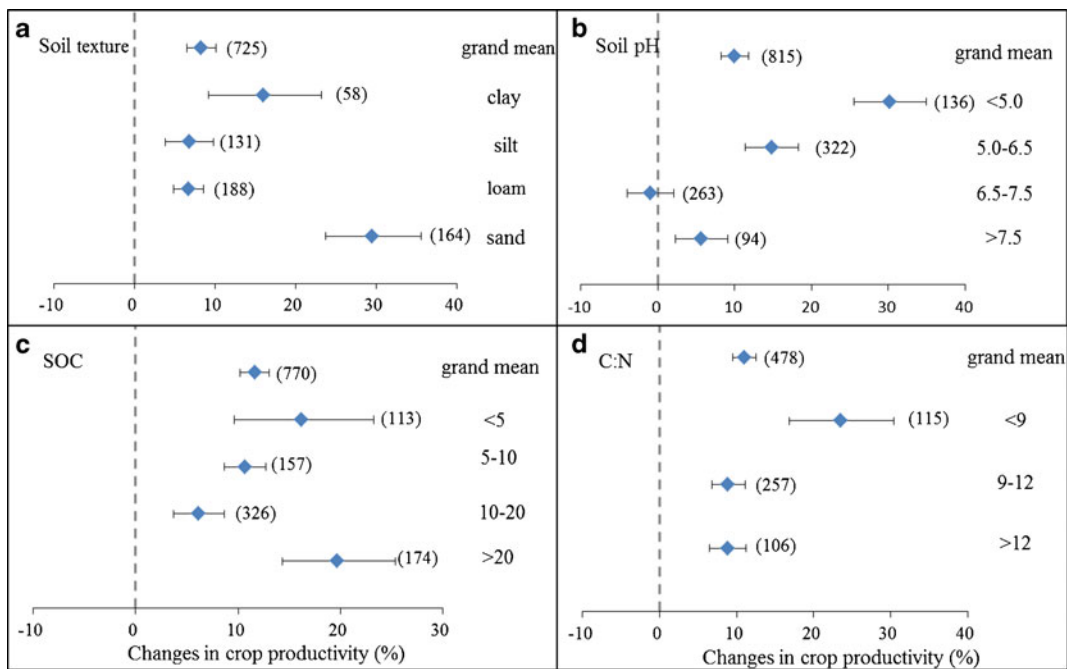


Fig. 8 Response of crop productivity to biochar additions expressed as the average percentage changes from control with 95 % confidence intervals for **a** soil texture, **b** soil pH, **c** SOC, and **d** soil C/N. The figures in brackets represent the numbers of data pairs

and magnitude of the crop productivity response (Figs. 9 and 10). Biochars used in the reported experiments were derived from almost 20 different types of biomass and were grouped here into six general types of crop residues, wood, manure, sludge, municipal waste, and mixtures of wood and sludge (Fig. 9a). Wood and crop residue biochars exerted consistent crop productivity increases respectively of 12.1 and 2.6 % on average, while manure biochar showed generally greater (29 %) but more variable responses across experiments. However, biochar from municipal waste significantly decreased crop productivity by 12.8 % on average. As shown in Fig. 10, crop productivity response was also dependent on the pyrolyzing temperature during biochar production. Greater crop productivity increases were seen with biochar produced at temperatures of >350 °C from wood and >550 °C for crop residues but at temperatures in a range of 350–550 °C for manure biochar.

Meanwhile, crop productivity responses were generally negative (–7.9 % on average) with non-alkaline (pH $<$ 7.0) biochars though generally positive with alkaline biochar (pH $>$ 7.0) (Fig. 9b). Finally, crop productivity changes with BSA were not shown to be proportional to biochar application rate up to 20–40 t ha $^{-1}$ although

the crop productivity increase diminished at biochar application rate of >40 t ha $^{-1}$ (Fig. 9c).

Discussion

General role of BSA in increasing crop productivity

Overall, this analysis has demonstrated a convincing positive response of crop productivity to BSA, with a few negative responses limited to specific circumstances. The overall mean increase with biochar application in crop productivity of 11.0 ± 1.4 % is consistent with the 10 % reported previously by Jeffery et al. (2011). Many earlier studies on biochar focused on the potential of biochar from biowastes to mitigate GHG emissions in agriculture (Lehmann 2007; Spokas and Reicosky 2009; van Zwieten et al. 2009; Knoblauch et al. 2011; Singh et al. 2010; Sohi et al. 2010; Taghizadeh-Toosi et al. 2011; Vaccari et al. 2011; Liu et al. 2012). Recently, Sohi (2012) addressed co-benefits of biochar for soil and environmental quality, plant nutrition, and health as well as ecosystem functioning. The significant and persistent increase in crop productivity with BSA suggests a major benefit for

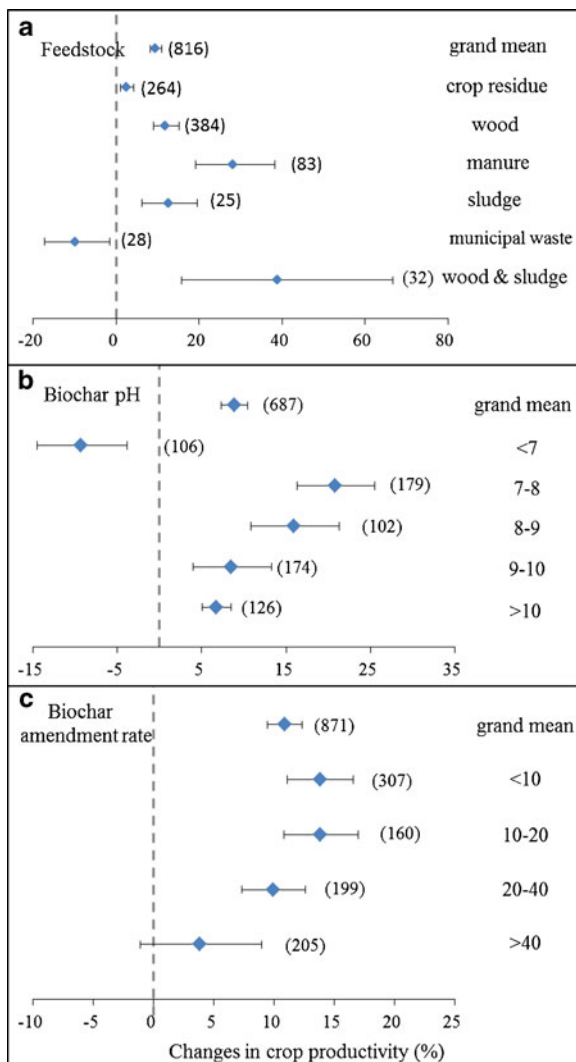


Fig. 9 Response of crop productivity to biochar additions expressed as the average percentage changes from control with 95 % confidence intervals for **a** biochar feedstock, **b** biochar pH, **c** biochar application rate (in tons per hectare). The figures in brackets represent the numbers of data pairs

agricultural production besides its role in mitigating GHG emission. BSA could provide a practical option to meet the challenge of food security in a changing climate.

Biochar's role in improving soil fertility

Enhancement of crop productivity with BSA has been attributed to soil fertility improvement via enhanced availability of basic nutrients such as Ca and Mg in acid soils (Glaser et al. 2002; Major et al. 2010),

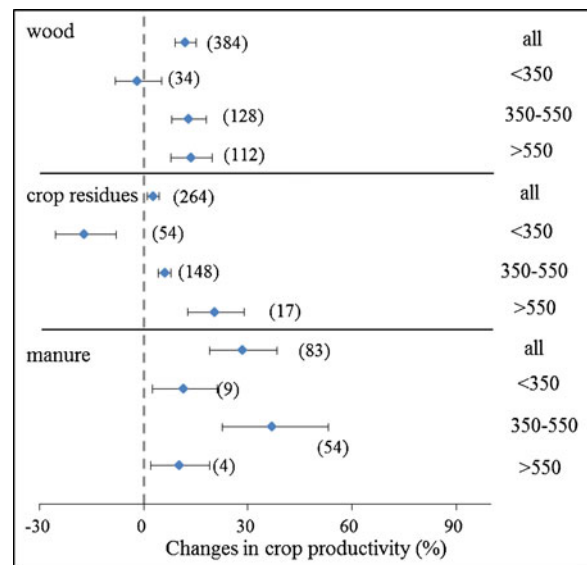


Fig. 10 Response of crop productivity to biochar additions expressed as the average percentage changes from control with 95 % confidence intervals for pyrolyzing temperature. The figures in brackets represent the numbers of data pairs

increased N retention and N-use efficiency (Hossain et al. 2010; van Zwieten et al. 2010; Zhang et al. 2010), increased enzymatic activity (Paz-Ferreiro et al. 2012) and improvement of soil moisture regime (Zhang et al. 2012b). The data reviewed here provide further insights into biochar's role in soil fertility and crop performance.

Liming effect

Glaser et al. (2002) highlighted biochar's role in increasing soil pH through a liming effect. In this study, the highest crop productivity increase under BSA was found for very acid soils (Fig. 8). This was further supported by the finding that amendment of non-alkaline biochar (pH<7) failed to increase crop productivity (Fig. 10). Jeffery et al. (2011) noted a soil pH increase of 0.1–2.0 units after biochar was applied to soils that have a wide range of pH values. The acid and very acid soils covered in this study were mostly from tropical and subtropical regions. In these areas, crop growth has been constrained by low availability of Ca, Mg, P, K, and by low levels of soil organic matter that has been accelerated by enhanced mineralization under a warming climate (Glaser et al. 2002). With an increase in soil pH, availability of K and P could be enhanced (Asai et al. 2009) and toxicity of Al

greatly decreased (Yamato et al. 2006; Steiner et al. 2007; Major et al. 2010). The liming effect of biochar not only improved mineral nutrient supply for plant growth but also alleviated Al and P stress for better crop health in acid tropical soils.

Soil aggregating and moistening effect

The highest and most consistent crop productivity increase (29.6 ± 5.9 %) through application of biochar in this study was found in sandy soils. In contrast, Jeffery et al. (2011) reported high responses of crop productivity to BSA in “medium” textured (12 % response on average) and “coarse” textured soil (10 % response on average) compared with no change in “fine” texture soils. The sandy soils included in our database were generally low in SOC (7.1 g kg^{-1} on average) and in total N (0.8 g kg^{-1} on average) and had a poor capacity to retain nutrients (CEC, 3.0 cmol kg^{-1} on average) and moisture. The high-productivity increase with BSA in sandy soils reported here could be a result of the greatly enhanced organic matter storage, which could have promoted soil aggregation and retention both of nutrients and moisture (Oguntunde et al. 2004; Gaskin et al. 2010; van Zwieten et al. 2010). The productivity increase also in clay soils (Fig. 8), however, could be mainly attributed to a soil aggregating effect and, in turn, reduced soil bulk density effects (Bengough et al. 2006), rather than to increased CEC and nutrient retention alone.

Persistence of BSA's effect

In field experiments, the biochar effect on crop growth varied over the years after a single amendment (Major et al. 2010; Haefele et al. 2011; Lentz and Ippolito 2011; Zhang et al. 2012c). Biochar's effect on crop productivity could be sustained (Zhang et al. 2012c) or even improved (Major et al. 2010) in the subsequent years after BSA. Here, as demonstrated in Fig. 5, a positive effect of biochar on crop productivity could persist for at least 2 years after amendment. The beneficial effects of using biochar in croplands have often been discussed in relation to the recalcitrant nature of the C entering the soil. The biochar-derived C storage has been considered possible for hundreds of years in Terra Preta from the Amazon Basin (Lehmann et al. 2006; Woolf and Lehmann 2012). Moreover, the half-life time of residual C from man-made biochar in soil

could be even in a millennium scale when its O/C molar ratio was <0.2 (Spokas 2010). Thus, biochar-stored C could act as a long-term soil conditioner with benefits for improved soil structure and/or soil moisture regime, which could have favored crop production as in the case of Terra Preta (Woolf and Lehmann 2012). Thus, applying biochar to soil from biowaste as stable organic C would be a promising option not only for sequestering C (Woolf et al. 2010) but also for enhancing food production in responsive soils in the longer term (Lehmann 2007). Therefore, longer-term field trials are required to determine the actual potential of biochar.

Effect of biochar properties on crop response

The response of crop productivity was shown to vary with biochar type related to the type and treatment of the feedstock (Fig. 9). It had been well known that both the physicochemical properties and nutrient contents of biochar are affected by the feedstock type (Spokas and Reicosky 2009; Qin et al. 2012). While biochar from wood and crop residues exerted consistent positive yield increase, the greatest mean increase was observed with manure biochar. Manure biochars have been generally considered very significant for improving soil fertility by promoting soil structure development (Joseph et al. 2010) in addition to their large amounts of plant available nutrients (Hass et al. 2012). The negative effects with municipal waste biochar observed in this study were dominated by the results of Rajkovich et al. (2012) who reported a great decline in crop productivity by 80 % under food waste biochar amendment at a high rate of 90 t ha^{-1} . The food waste biochar contained sodium ten times as much as wood and straw biochar, which increased soil salinity and inhibited plant growth.

Crop productivity was significantly increased with biochar produced at higher pyrolyzing temperatures (Fig. 10), presumably as a result of the liming effect as biochar pH generally increases with increasing temperature for pyrolysis (Rakovich et al. 2012). However, there was an interaction of feedstock and pyrolysis temperature on crop productivity to BSA. Biochars via pyrolysis at both low and higher temperatures generally contained very limited N. In particular, pyrolyzing at temperature higher than $450 \text{ }^\circ\text{C}$ would result in losses of N in manure biochar. High nutrient contents and crop yields were found with manure biochar pyrolyzed at

temperatures of <500 °C compared with more recalcitrant biochar produced at even higher temperatures (Chan et al. 2008).

Economics of BSA

Biochar amendment is an emerging practice to improve soil crop productivity and mitigate climate change by sequestering C in soils. However, its economic feasibility could be constrained by the high price of biochar, and low price of C traded in the market. For example, large-scale biochar production from crop straw is now commercially available in China (Pan et al. 2011), but the price of biochar is as high as 1,800 CNY t⁻¹ (www.sanlinxinnengyuan.com). Biochar amendment even at a low rate of 10 t ha⁻¹ would cause a cost of 6,000 CNY/year if the effect could be sustained for 3 years. Assume C benefits to be traded with US\$25 (150 CNY)/t of CO₂ equivalent, the biochar cost would still be over 5,000 CNY ha⁻¹. The normal yield of rice and wheat in China could be about 10 t ha⁻¹, and the price for japonica brown rice regulated by the state is 3,000 CNY t⁻¹, so even a high yield increase by 15 % would result in an economic gain from BSA of only 4,500 CNY ha⁻¹. Currently, at least in this Chinese example, the high cost of biochar would not be balanced by the potential economic gain based on average yield improvements and current prices. Joseph et al. (2013) report that reaction of approximately 110 kg ha⁻¹ of wheat straw biochar with 340 kg ha⁻¹ of NPK fertilizer can result in yield increases of rice yield of more than 25 % compared with the application of 450 kg ha⁻¹ of NPK fertilizer only. At these low biochar application rates the economic benefits outweigh the costs of replacing approximately 25 % NPK fertilizer with biochar.

Conclusions

This analysis, by reviewing 103 studies published before 1st April 2013, shows a significant increase of crop productivity with 8.4 % for crop yield and 12.5 % for aboveground biomass. Greater effects on crop productivity were found for dry land crops than for paddy rice, in acid rather than in neutral, and in sand or clay than in loam soils, likely due to the liming and moistening effects of biochar. Manure, wood, and straw biochars exerted consistent positive yield increases compared with biochars prepared from other feedstocks. The

difference in crop productivity responses to BSA between pot and field experiments suggested that biochar effects on crop productivity could be overestimated using pot or greenhouse experiment. Overall, the use of biochar, particularly of manure, wood, and crop straw, as soil amendment could be a promising approach to enhance crop yield. While BSA's effect on crop productivity persisted for at least 2 years in a limited numbers of field experiments, well-designed long-term field studies are warranted to explore the long-term effects and the mechanisms across a wide range of soil, crop, and biochar conditions. Optimizing biochar's crop productivity effects and benefits to establish economic feasibility should be among the innovation priorities in the future biochar science and technology development in world agriculture.

Acknowledgments This work was financially supported by NSFC under a grant 40830528 and by Ministry of Agriculture under a grant 2110402-201261. We are grateful to the authors of the literature cited for their constructive original research and the information provided for this analysis. Thanks also go to the audience comments given at preliminary presentations of this work at workshops related to biochar issues in 2012.

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