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Title: Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls

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Abstract

The added value of biochar when applied along with fertilizers, beyond that of the fertilizers themselves, has not been summarized. Focusing on direct comparisons between biochar additions (≤ 20 t ha^{-1}) – separately considering the addition or not of inorganic fertilizers (IF) and/or organic amendments (OA) along with biochar – and two different controls (with and without the addition of IF and/or OA), we carried out a meta-analysis to explain short-term (1-year) field responses in crop yield across different climates, soils, biochars, and management practices worldwide. Compared with the non-fertilized control, a 26% (CI:15-40%) increase in yield was observed with the use of IF only, whereas that of biochar along with IF caused a 48% (CI:30-70%) increase. Compared to the use of IF only, the addition of biochar along with IF caused a 15% (CI:11-19%) increase in yield, indicating that biochar was as effective as fertilizers in increasing crop yields when added in combination. The use of biochar alone did not increase crop yield regardless of the control considered. Whereas in the short-term liming may have partly contributed to the beneficial effect of biochar (>90% was plant-derived) when added along with IF, a separate meta-analysis – using those studies that reported crop yields for different years after a single biochar application – showed a 31% (CI:17-49%) increase in crop yield observed over time (≥ 3 years), which denotes the influence of biochar properties other than liming (i.e., an increase in CEC). Our results also suggest that biochar application rates > 10 t ha^{-1} do not contribute to greater crop yield (at least in the short term). Data limitations precluded identification of the influence of feedstock, production conditions, or climatic conditions without bias. As the response of crop yield to biochar addition was less a result of climatic zones or soil type than fertilizer use (chiefly N additions), the choice of nutrient addition along with biochar should be priorities for future research and development regardless of the region.

Keywords: biochar, meta-analysis, crop yield, inorganic fertilizer, organic amendment.

1. Introduction

The future of agriculture faces massive challenges, such as the need to (i) produce enough food for the growing global population (Godfray *et al.*, 2010; Foley *et al.*, 2011), (ii) reduce the environmental footprint of agricultural intensification brought by the "green revolution", which has transgressed planetary boundaries (Steffen *et al.*, 2015; Hall-Spencer, 2017), and (iii) decrease the growing dependency on phosphate rock, which is non-renewable (Elser & Bennett, 2011). Despite the magnitude of the challenges, there are opportunities to overcome them by further intensifying agriculture while reducing nutrient imbalances and inefficiencies (Mueller *et al.*, 2012; Withers *et al.*, 2015). One such opportunity is biochar technology, which can contribute to the recovery of nutrients from waste yet still increase crop yields, while abating climate change (Woolf *et al.*, 2010; Woolf *et al.*, 2016). However, an improved understanding of the mechanisms through which biochar influences crop yield is still needed so that decision-support tools aimed at matching the most suitable biochar for a specific cropping system are developed. This will help biochar systems to become attractive to farmers and land managers, who will only add biochar to their soils if crop yields increase, and allow this technology to be better positioned to compete with other climate change mitigation strategies that use biomass, such as bioenergy systems, bioenergy with carbon capture and storage (Woolf *et al.*, 2016; Woolf *et al.*, 2018).

Multiple benefits of biochar application to soil under cropping systems include provision of nutrients (Wang *et al.*, 2012a; Camps-Arbestain *et al.*, 2015), and improvement in soil properties and conditions, such as water holding capacity (Novak *et al.*, 2012; Herath *et al.*, 2013), cation exchange capacity (CEC) (Glaser *et al.*, 2002), and pH (Singh *et al.*, 2017). The benefits that are associated with the ash fraction of biochar, such as the direct provision of nutrients and liming potential, are short-lived, whereas those imparted by the biochar structure (i.e., water holding capacity, CEC) are long-lasting (Woolf *et al.*, 2018). Meta-analysis studies have estimated average yield increases by a grand mean of 10% (Jeffery *et al.*, 2011), 11% (Liu *et al.*, 2013), 17% (Jeffery *et al.*, 2015), and 9% (Jeffery *et al.*, 2017). Yield responses have been found to be relatively larger in low-pH and coarse-textured soils, and with the application of nutrient-rich biochars (Jeffery *et al.*, 2011; Biederman & Harpole, 2013; Liu *et al.*, 2013), or in soils with small CEC and low levels of organic carbon (OC) content (Crane-Droesch *et al.*, 2013), particularly in the tropics (Jeffery *et al.*, 2017). Data variability in some of these studies is generally large and the extent to which this is related to manageable variability or to uncertainty is unclear. One important explainable cause of variation is the use of inorganic or organic nutrient additions together with biochar. In previous meta-analysis studies, the application of biochar was the only difference between controls and treatments (Jeffery *et al.*, 2011; Liu *et al.*, 2013; Jeffery *et al.*, 2017) and thus these studies included a variety of control treatments, regardless of whether the controls received fertilizers or not. Furthermore, the earlier studies did not separately compare biochar alone with a 'business-as-usual' fertilized control. The possibility of separately considering the types of amendment received in both the treatment and the control should allow us to discern the added value of biochar on crop yield when applied along with 'business-as-usual' fertilizers.

In this study, we have investigated biochar effects on crop yield by separately comparing against (i) a control without inorganic fertilizer (IF) and/or organic amendment (OA), and (ii) a control with either IF and/or OA. In the second comparison, biochar treatments were identical to the control but for the application of biochar, with the only exception being when a comparison was made between biochar application alone and the fertilized control. Also, a third comparison was carried out between the two controls so that the specific effect size of adding only fertilizer (IF and/or OA) to the investigated soils could be evaluated. We only used data from field studies that had received a biochar application of ≤ 20 t ha^{-1}, so that results can be readily extrapolated for biochar applications to common field situations.

2. Materials and methods

2.1 Data Collection

We collected data from relevant peer-reviewed publications. The publications were identified using the online databases – ISI Web of Science and Google Scholar between 1998 and 2017. Publications were identified using the key words "biochar" or "charcoal" AND "field trial" AND "crop yield" OR "crop productivity" OR "plant growth". In the main meta-analysis, only biochar application rates ≤ 20 t ha^{-1} and crop yields within the first year of biochar application were considered. Separate meta-analyses were carried out for studies that included (i) application rates up to 40 t ha^{-1}, and (ii) multiple years of observations in relation to crop yield after biochar application. We selected studies that reported crop yield, biochar properties, and soil properties for at least two types of treatments: (a) those that did not receive any biochar, inorganic fertilizer (IF), or organic amendments (OA), referred to as "non-fertilized control"; OR (b) those where only either IF, OA, or both IF and OA, were applied, referred to as "fertilized control"; AND (c) where biochar with or without supplemental IF and/or OA was used, referred to as the "treatment", and identified as either biochar, biochar+IF, biochar+OA or biochar+IF+OA, as appropriate. When comparing the biochar treatments with the "fertilized control", (i) biochar and biochar+IF treatments were compared with IF only (control), (ii) biochar+OA treatment was compared with OA only (control), and (iii) biochar+IF+OA treatment was compared with IF+OA only (control).

Altogether, more than 100 studies were reviewed, and we selected 56 studies (Blackwell *et al.*, 2010; Kimetu *et al.*, 2008; Steiner *et al.*, 2008; Asai *et al.*, 2009; Gaskin *et al.*, 2010; Major *et al.*, 2010; Solaiman *et al.*, 2010; Zhang *et al.*, 2010, 2012a; 2012b, 2013, 2016; Baronti *et al.*, 2010; Islami *et al.*, 2011; Sukartono *et al.*, 2011; Liu *et al.*, 2012, 2014a, 2014b, 2016; Cornelissen *et al.*, 2013; Güereña *et al.*, 2013; Hammond *et al.*, 2013; Masto *et al.*, 2013; Slavich *et al.*, 2013; Suddick & Six, 2013; Martinsen *et al.*, 2014; Mekuria *et al.*, 2014; Tammeorg *et al.*, 2014a; 2014b; Watanabe *et al.*, 2014; Bian *et al.*, 2014; Abiven *et al.*, 2015; Agegnehu *et al.*, 2015, 2016a, 2016b; Li *et al.*, 2015, 2017; Nelissen *et al.*, 2015; Vaccari *et al.*, 2015; van Zwieten *et al.*, 2015; Xiang *et al.*, 2015; Mierzwa-Hersztek *et al.*, 2016, 2017; Paneque *et al.*, 2016; Backer *et al.*, 2016; Cui *et al.*, 2017; Faloye *et al.*, 2017; Gautam *et al.*, 2017; Griffin *et al.*, 2017; Haider *et al.*, 2017; Horák *et al.*, 2017; Koga *et al.*, 2017; Arif *et al.*, 2017; Yeboah *et al.*, 2017; Si *et al.*, 2018; Vitkova *et al.*, 2017), which met our criteria described above (studies included in the meta-analysis are marked with an asterisk in the cited literature). The selected studies represented a range of geographical and environmental characteristics (64 experimental locations in 24 different countries; Supplementary Information; Figure S1), and we used 264 observations in the meta-analysis.

We extracted meta-data from each of the selected publications, including climatic, temporal (i.e. year of observation), soil chemical, physical and biological data, measurement units, treatments, and analytical methods. The specific data included in the meta-analysis were: crop productivity (grain yield for cereal crops, aboveground biomass, fruit yield and tuber or bulb yield), climatic conditions, soil properties (soil classification, soil texture, initial soil pH, OC and CEC), biochar production conditions (type of feedstock and highest heating temperature (HHT) used for pyrolysis), biochar application rates, type of treatment (i.e., addition of biochar with or without IF and/or OA), and nitrogen (N) application rates additional to biochar application. Where data were available in a graphic form only, the values were extracted using Plot Digitizer 2.6.2 (Huwaldt & Steinhorst, 2012). The categorical variables (crops, climate, texture, soil order, initial soil pH, initial OC, initial CEC, type of feedstock, biochar pH, biochar application rate, other amendments added along with biochar, N application rate additional to biochar application) were then grouped into different categories, which are described in Table 1 along with a description on how data were harmonized. For example, soil pH values were converted to pH measured in water using a 1:2.5 (wt:v) ratio following Lierop (1981), Conyers & Davey (1988), and Kabala *et al.* (2016). Values of CEC were used as provided by the authors given that methods used for CEC measurements were not always reported. When reported, 1 N ammonium acetate at pH 7 was the method most commonly used (Supplementary information; Table S1).

2.2 Meta-data analysis

Statistical analyses and graphical representation were performed according to Hedges *et al.* (1999) and Cayuela *et al.* (2014) using Meta Win 2.0 software (Rosenberg *et al.*, 2000). This meta-analysis was conducted to characterize the crop yield response to biochar application by comparing the treatments to either the “unfertilized control” or the “fertilized control”. We used natural log-transformed response ratio (R) as a measure of the effect size:

$$\ln \mathrm{R} = \ln \left(\frac{\mathrm{XE}}{\mathrm{XC}}\right)$$

Where

XE is the mean value of treatment; and XC is the mean value of control (either of the two controls considered). Mean effect sizes of each category and the 95% confidence intervals (CIs) were generated by bootstrapping (999 iterations) using MetaWin 2.0 Statistical software (Rosenberg *et al.*, 2000). When the two controls were available for the same observation, we also ran the MetaWin 2.0 software considering XE the mean value of the “fertilized control” and XC the mean value of the “non-fertilized control”.

A non-parametric function, based on the sample size (the number of replications) was used for weighting (Adams *et al.*, 1997). We chose this function instead of the variance because many studies did not report a measure of variance for crop yield. The sample-size weight function used here was:

$$\text{Weight} = \frac{N_E \times N_C}{N_E + N_C}$$

where N_E is the number of replicates of the experimental observation and N_C is the number of replicates of the control observation (either of the two controls considered) within the same experimental conditions (i.e. study). A categorical random effects model was used to calculate the grouped effect sizes. The pooled variance of the yield was ≤ 0, for which MetaWin 2.0 software automatically switched from a categorical random model to a categorical fixed model.

Graphically, the change in yield is shown as a proportion of the control (the effect size was exponentially transformed, then R–1 was calculated and multiplied by 100 to obtain the percentage change). The relative changes in crop yield within each category were considered to be significant from one another if their CIs did not overlap. The overall mean of the crop yield changes (either for each category or for the whole observation) was considered to be significantly different from the controls (either of the controls considered), if the 95% CI did not overlap with zero (Scheiner & Gurevitch, 2001). When the size of groups was n < 10, these were dropped from the analysis. The dataset used to generate different graphs are reported in the Supplementary Information (Tables S2, S3, S4, S5 and S6).

3. Results

3.1 Effect of Biochar on the Grand Mean.

The results showed a significant grand mean increase in yield of 28.7% (Bootstrap CI 95%: 19.0–40.5%, n = 150) with biochar application (with and without IF and/or OA) as compared with the "non-fertilized control" (Figure 1). The grand mean increase in crop yield of the "fertilized control" when compared with the "non-fertilized control" was 29.8% (Bootstrap CI 95%: 18.9–42.7; n = 118) (Supplementary information Figure S2). The change in yield relative with biochar application (with and without IF and/or OA) to the "fertilized control" (see Materials and methods for details on compared treatments) was expectedly smaller, but still significant ($P < 0.05$), with a grand mean increase of 9.9% (Bootstrap CI 95%: 5.3–14.4%, n = 232) (Figure 2). The variables that had the greatest influence on crop yield were related to biochar properties, initial soil properties, and biochar application conditions (i.e., the simultaneous addition of IF along with biochar, the amount of N fertilizer added) (Figures 1 and 2). With few exceptions, other categorical variables (climate, biochar application rate) had a generally smaller contribution to the variance.

3.2 Effect of Biochar Properties.

The type of biochar feedstock significantly contributed to the variation on yield responses, with the biochars produced from cereal residues causing the largest mean yield increase. This was 90.4% (Bootstrap CI 95%: 48.9–135.5%, n = 33) compared to the "non-fertilized control"

(Figure 1), and 23.7% (Bootstrap CI 95%: 15.9–32.7%, n = 75) when compared to the "fertilized control" (Figure 2). Biochars from animal and human wastes also increased crop yield, with a mean effect size of 11.2% (Bootstrap CI 7.4–15.6, n = 13) as compared to the "fertilized control" (n was < 10 in the comparison with the other control). The other two types of feedstock tested, papermill residue and ligneous material, had a non-significant effect size, except for the ligneous material when compared with the "non-fertilized control" (Figures 1 and 2).

The HHT also had a significant influence on the yield effect size, with biochars produced under < 400 °C causing a mean increase of 97.4% (Bootstrap CI 95%: 39.1–161.6%, n = 21) (Figure 1) and 26.5% (Bootstrap CI 95%: 10.8–40.6%, n = 49) (Figure 2) as compared to the "non-fertilized" and "fertilized" controls, respectively. The corresponding effect sizes of the biochars pyrolyzed at temperatures ranging from 400 to 550 °C were ca. three times smaller. Biochars produced at temperatures >550 °C caused an even smaller effect in yield than the biochars produced at 400 to 550 ℃ (<18 and <3%, compared to the "non-fertilized" and "fertilized" controls, respectively; Figures 1 and 2), which were not significantly different to the "fertilized control".

3.3 Effect of Initial Soil Properties.

Soils with sandy texture had the greatest crop yield response to biochar addition (with and without fertilizer) with a mean yield increase of 108.4% (Bootstrap CI 95%: 42.8–183.7%, n = 17) compared with the "non-fertilized control" (Figure 1); this response was significantly greater than that in loamy textured soils. The greatest response to the use of fertilizer only was in sandy soils, with a mean increase in yield of 102.7% (Bootstrap CI 95%: 60.0–152.6; n = 17) (Supplementary information Figure S2). However, no significant differences were observed between the textural classes when the yield response of the biochar treatment was compared to the "fertilized control" (Figure 2).

The application of biochar (with and without fertilizer) to small CEC (< 100 $mmol_c\ kg^{-1}$) soils resulted in the greatest increase in crop yield as compared to the "non-fertilized control" with a mean effect size of 160.9% (Bootstrap CI 95%: 85.1–245.1%, n = 12) (Figure 1). There were no significant effects of biochar application (with and without fertilizer) in soils with CEC >

200 mmol$_c$ kg^{-1} (Figure 1). Small CEC soils were also those that had the greatest response to the use of fertilizer only, with a mean increase in yield of 111.3% (Bootstrap CI 95%: 58.7–173.1; n = 11) (Supplementary information Figure S2). The use of fertilizer only resulted in no positive effect on yield in soils with CEC > 100 mmol$_c$ kg^{-1} (Supplementary information Figure S2). Neither were significant differences in yield response observed between CEC classes when compared to the "fertilized control" either (Figure 2).

Small initial soil OC concentrations (OC ≤ 20 g kg^{-1}) were associated with a larger response in crop yield to biochar addition (with and without fertilizer), with a mean effect size of 34.3% (Bootstrap CI 95%: 21.8–30.3%; n = 128) and of 11.5% (Bootstrap CI 95%: 6.0–16.6%; n = 184) compared with the "non-fertilized" and "fertilized" controls, respectively (Figures 1 and 2). However, the differences in yield response between OC rates (OC ≤ 20 vs. > 20 g kg^{-1}) were only significant in comparison with the "non-fertilized control".

The influence of initial soil pH on the yield effect size was greater when the soil pH was ≤ 6.5 than in soils with pH values > 6.5 (Figures 1 and 2). Yet no significant differences between pH groups (pH ≤ 6.5 vs. > 6.5) were detected. We carried out a more detailed meta-analysis, after grouping biochar pH values (≤ 9 vs. > 9) and then evaluated their effect depending on the initial soil pH values (either ≤ or > 6.5) (Figure 3). Crops grown on soils with pH ≤ 6.5 always had a positive yield response to biochar addition, regardless of the biochar pH value. In contrast, no positive effect size was observed compared to the "fertilized control" when biochars with a pH > 9 were added to soils with initial pH values > 6.5 (Figure 3). When considering the influence of the use of fertilizer only (without biochar) on the effect size of crop yield, no significant differences between soil pH classes were detected (Supplementary information; Figure S2).

3.4 Effect of Pedoclimatic Conditions.

In comparison with the "non-fertilized control", the addition of biochar to relatively young (Entisols + Inceptisols) and highly weathered (Ultisols + Oxisols) soils produced larger effects on yield than biochar applications to other soil types (Alfisols + Cambisols, Paddy soils), with an increase of 75.1% (Bootstrap CI 95%: 29.1–143.0%, n = 23) and 46.6% (Bootstrap CI 95%: 26.2–71.3%, n = 37), respectively. However, the differences between soil types were significant only between relatively young soils (Entisols + Inceptisols) and the group of Paddy soils (Figure 1). In fact, crops on Paddy soils were the only ones that did not respond to the addition of fertilizer alone (Supplementary information Figure S2). Relative to the "fertilized control", no clear influence of soil order was observed (Figure 2).

Crops growing under tropical and subtropical climates showed greater responses in yield than those under other climates, with a mean effect size of 40.6% (Bootstrap CI 95%: 20.7–64.7, n = 72) and 14.8% (Bootstrap CI 95%: 7.2–21.8, n = 127) compared to "non-fertilized" and "fertilized" controls, respectively (Figures 1 and 2). However, this climatic group was only significantly different from the continental + humid-temperate climates when compared with the "fertilized control" (mean effect size of 0.2%; Bootstrap CI 95%: −3.1–3.8, n= 51). Crops grown under Mediterranean-type climate had a mean effect size of 23.3 and 2.3% when compared with the "non-fertilized" and the "fertilized" control, respectively (Figures 1 and 2), with the differences in yield responses not being significant from the other climatic groups considered.

3.5 Responses of Crop Types.

When compared to the "non-fertilized control", maize showed the greatest response to biochar addition (with and without fertilizer) with a significant mean increase of 95.5% (Bootstrap CI 95%: 48.7–151.8%, n = 30), followed by wheat, barley or oat (mean: 29.2% Bootstrap CI 95%: 16.8–46.6%, n = 49), whereas there was no significant increase in yield of rice and rapeseed/sunflowers (Figure 1). A similar order in the response of crop types (maize > wheat or barley or oat > rice) was observed when evaluating the effect of fertilizer use alone (Supplementary information; Figure S2). In comparison with the "fertilized control", legumes crops had the greatest response with a significant mean increase of 27.2% (Bootstrap CI 95%: 8.7–49.5%, n = 17), but this response was only significantly different from the wheat, barley or oat crop group (Figure 2). There was no effect size in the growth of these cereals to biochar addition as compared to the "fertilized control".

3.6 Effect of Application Rates and Simultaneous Addition of Other Amendments.

In the main meta-analysis, only application rates $\leq$ 20 t ha^{-1} (applied in year 1) were considered. Significant differences between the 5-10 and 10-20 t ha^{-1} groups were only observed when compared with the "fertilized control" (Figure 2), with their mean effect sizes being 18.5% (Bootstrap CI 95%:11.2–26.0%, n = 84) and 0.9% (Bootstrap CI 95%: –8.9–10.4%, n = 67), respectively. No significant differences were observed between categories in comparison with the "non-fertilized control" (Figure 1). Larger application rates (> 20 t ha^{-1}) of biochar were considered in a separate meta-analysis, where application rates ≤ 20 and > 20 t ha^{-1} were compared by including only those studies that tested both high and low rates (Figure 4). No significant differences between application rate classes were detected by this analysis.

When only IF was used (no biochar addition), mean increase in crop yield was 26.3% (bootstrap CI 95%: 14.9-39.7, n = 106) compared with the "non-fertilized control" (Supplementary information; Table S7). When biochar was added without the simultaneous use of IF, there was no significant effect size on crop yield in comparison with either of the controls considered (Figures 1 and 2). In contrast, the addition of biochar + IF had a significant mean effect size of 47.5% (bootstrap CI 95%: 29.6−70.3%, n = 78) and of 14.5 (bootstrap CI 95%: 10.5−19.1%; n = 167) when compared to the "non-fertilized" and "fertilized" controls, respectively (Figures 1 and 2). The application of N fertilizer along with biochar had a substantial effect on crop yield, with N application rates between 100 and 200 kg ha^{-1} yr^{-1} producing the largest mean effect sizes when compared with the "non-fertilized control" (mean effect size of 145.2%; bootstrap CI 95%: 91.0–209.1%, n = 20). In comparison with the "fertilized control", N application rates ≤ 200 kg ha^{-1} yr^{-1} resulted in the largest mean effect sizes (13.8 and 13.4% for the ≤100 and 100–200 kg ha^{-1} yr^{-1} groups, respectively) (Figures 1 and 2).

3.7 Changes in Crop Yield Effect Sizes Over Time.

Those studies (22) that reported crop yields for different years after biochar application (only a single application was taken into account) were used to investigate whether the crop effect size changed over time (Figure 5). Over the study period considered (with a maximum of 4 years), the addition of biochar (with and without fertilizer) produced a significant mean increase in crop yield of 55.2% (Bootstrap CI 95%: 33.4–80.0%, n = 68) compared with the "non-fertilized control". The largest mean increase in crop yield with biochar application was observed in the second year (mean = 105.0 %; bootstrap CI 95%: 59.2–177.3%, n = 27), followed by the first year (mean = 48.1 %; Bootstrap CI 95%: 20.5–81.6%, n = 20), both being significantly greater than the "non-fertilized control" (Figure 5a). No effect on crop yield was observed three years after biochar application.

When compared to the "fertilized control", the addition of biochar (with or without fertilizer) did not result in a significant mean increase in crop yield (7.2%; bootstrap CI 95%: –0.8–15.2%, n = 170) over the period considered. In contrast to the "non-fertilized control", a significant effect on crop yield compared to the "fertilized control", was only observed after three years of biochar application (mean = 30.5%; Bootstrap CI 95%: 16.6–48.5%, n = 44) (Figure 5b).

4. Discussion

4.1 Effect of Biochar on the Grand Mean.

In this meta-analysis, the use of two different controls ("non-fertilized" vs. "fertilized") along with the comparison between the two controls, and the carefully selected categorical variables allowed us to explain the variability in crop yield responses from biochar application to soil. In the comparison to the "non-fertilized control" (grand mean: 29%), basically all confidence intervals appear on the positive side (Figure 1), which implies that, biochar addition to soil generally produced positive effects on crop yields. However, biochar would not be expected to fully replace IF and/or OA (Jeffery *et al.*, 2015; Camps-Arbestain *et al.*, 2015), as made evident when compared with the "fertilized control". The grand mean obtained when comparing the biochar-treated soils with the "fertilized control" (10%; CI 95%: 5-14%; n = 232) was similar to the grand means reported in previous meta-analyses, except for one study: 10% (CI 95%: 7-13%; n = 782) (Jeffery *et al.*, 2011), 11% (CI 95%: 9-12%; n = 880) (Liu *et al.*, 2013), 17% (CI 95%: 15-19%) (Jeffery *et al.*, 2015), and 9% (CI 95%: 7-11%; n = 1125) (Jeffery *et al.*, 2017).

4.2 Effect of Biochar Properties.

Apparently, the most distinct effect of biochar properties on crop yields was caused by pyrolysis temperature, with biochars produced at ≤ 400 °C causing the greatest increase in crop yield. Biochars in this category were mostly produced from cereal residues (50% of observations) and ligneous material (32% of observations), and thus made of a "structural" type of feedstock with little fertilizer value (Jeffery *et al.*, 2017) and a small to intermediate liming value (Singh *et al.*, 2017), in contrast with animal and human wastes. At first glance, low-temperature biochars made from cereal residues increased crop yield by 50% (bootstrap CI 95%: 34.9−67.7%, n = 25) whereas those produced from ligneous material did not increase yields (mean: −12.7%; bootstrap CI 95%: −36.3−12.9; n = 16). However, after further analyses, this was proven to be an artifact caused by several masking effects, as described below. Biochars produced at HTT > 550 °C were dominated by ligneous material (87%) and, therefore, the results of HHT and type of feedstock at higher temperatures were masked by an unbalanced dataset. To overcome this limitation, we compared the effect size of biochars produced from cereal feedstocks only when pyrolysed at three different HHT (≤ 400 °C, 400–550 °C, > 550 °C). We found that the mean value progressively decreased as the HHT increased, with a mean effect size on yield of 50%, 8%, and –9%, respectively for the three HHTs. However, all studies in which biochars were produced from cereal residues at ≤ 400 °C were carried out in soils with pH ≤ 6.5, whereas 32% and 67% of the soils treated with biochars produced from cereal residues at HHT of 400–550 °C and > 550 °C, respectively, had initial pH values > 6.5. Therefore, the biochar effect of HHT and feedstock type on crop yield based on the currently available global biochar dataset should not be interpreted until more balanced data are available or the data can be stratified appropriately. The biochars produced from animal and human wastes also showed a positive effect on crop yield, which is consistent with previous meta-analyses (Liu *et al.*, 2013; Jeffery *et al.*, 2017) and their nutrient values (Camps-Arbestain *et al.*, 2015). However, a more in-depth analysis of these biochars was hampered by the small dataset available, and the effects of biochar properties should be interpreted with great caution.

4.3 Effect of Initial Soil Properties.

The remarkable positive response of crop yield to biochar addition in sandy soils or soils with a small CEC (> 100% yield effect size), and in soils with little OC, when compared with the "non-fertilized control" was expected, given the plant constraints under low nutrient (i.e., non-fertilized) conditions of the control. However, it should be noted that 56% of the observations considered in the comparison with the "non-fertilized control" included the use of fertilizer in addition to that of biochar. Thus the benefits could not solely be attributed to the effect of biochar, especially considering that the addition of fertilizer only to sandy soils or soils with a small CEC also caused yield effect sizes > 100%. The lack of any clear trend in crop yield response to biochar addition with respect to soil texture, CEC, or OC when compared with 'business-as-usual conditions' (i.e., "fertilized control") could be explained by the fact that beneficial effects of biochar in soil beyond direct nutrient supply or liming become more evident over time.

The fact that soils with initial pH values ≤ 6.5 tended to show greater yield increases than those with initial pH values > 6.5 is consistent with the liming value of biochar, which can contribute to improve the availability of plant nutrients (e.g., P) and reduce aluminium toxicity (Bolan *et al.*, 2001; Poschenrieder *et al.*, 2008). Yet differences between the two groups of soils (pH ≤ 6.5 vs. > 6.5) only became significant when rice crops were excluded from the meta-analysis (Supplementary information; Figures S3 and S4; Tables S7 and S8). The pH values of reduced soils (i.e., Paddy soils) should tend towards neutrality (Bohn *et al.*, 2002), which was not the case in > 90% of the observations considered. When the pH was reported, it was measured after air-drying the soil, which should have caused a lower pH reading than the true pH under field conditions, which explains why the effects of biochar on soil pH are more evident after excluding Paddy soils from the meta-analysis. It should be noted that a large fraction of the biochars considered in this study were made from plant residues (> 90%) as opposed to animal or human wastes, and thus their beneficial effects (liming and nutrient supply) may not be long-lasting and generally limited. The fact that applying a high-pH biochar to a high-pH soil rendered a negative yield effect size could be explained by the fact that increasing the pH of neutral or alkaline soils might decrease the availability of some nutrients (i.e., P, Mn, Zn) (Cornforth, 1998).

4.4 Effect of Pedoclimatic Conditions.

Larger positive response of crops growing under tropical and subtropical climate than those growing under continental and temperate climates (mean values: 14.8 vs. 1.4% when compared with the "fertilized control", respectively) is consistent with the published literature (Jeffery *et al.*, 2017). It should be noted, though, that in continental and temperate type climates, the dominant feedstock used was woody material (76% of the observations) whereas in areas under tropical and subtropical climates this dropped to 46% (and to 34% after eliminating rice paddies). So again, an unbalanced dataset could have contributed to these differences and thus the influence of climate should be interpreted with care. The effect size under tropical and subtropical climates reported by Jeffery *et al.* (2017) was 25% when both pot and field studies were included, but only 12% excluding pot studies. Other differences between the two studies include (i) discrepancies in the controls considered, (ii) the conditions forced in this study (i.e., biochar application rates ≤ 20 t ha^{-1}), and (iii) the fact that here climate was classified according to Köppen, whereas in Jeffery *et al.* (2017) climate was based on latitude (≤ 35 degree latitude vs. > 35 degree latitude) – yet when considering the latitude criteria in our study, the yield effect in the tropics was 13% (data not shown). Furthermore, in our study, other factors, such as biochar properties, soil properties, simultaneous addition of fertilizer, were found to be as relevant as, or more relevant, than climate. The overall larger effect of biochar amendments on crop yield observed under tropical and subtropical conditions than under continental and temperate climate is consistent with the (i) a prevalence of more weathered soils in the latter (yet this might not be that relevant given the results obtained when grouping based on soil orders; Figures 1 and 2), and (ii) geo-economic circumstances, with soils under continental- and temperate-type climates having historically received large application of fertilizers (Sattari *et al.*, 2012; Schoumans *et al.*, 2015), thus being closer to their maximum potential (Mueller *et al.*, 2012), as already alluded to by Jeffery *et al.* (2017).

4.5 Effect of Crop Types.

The generally small response of rice crops to biochar amendments is consistent with the results obtained by (Liu *et al.*, 2013), who reported a greater crop response for dryland crops (10.6% on average) than for paddy rice (5.6% on average). It is possible that common structural benefits provided by biochar to soils (i.e., increase in water retention) were not relevant under flooded conditions. Also, as mentioned above, pH of reduced soils tends towards neutrality (Bohn *et al.*, 2002), and thus addition of a liming material, such as most of the biochars considered here, might not provide benefits to this crop. Yet in this study, rice crops were less responsive to the use of fertilizer only, and thus it is possible that the sites considered were close to their potential rice yield. Maize had a generally larger response than other dryland cereals (wheat, barley, oat), especially when compared with the "non-fertilized control"; however, the differences could be related to geographic locations as most studies on maize were carried out in the tropical and subtropical regions, whereas those of wheat, barley and oat were predominantly under Mediterranean or continental and temperate climates. Information on crop yield for legumes, mixed vegetables (tomato, broccoli, babocha bok choy, coriander, lettuce, spinach, chilly), and tubers and bulbs was available for the comparison with the fertilizer control. All tended to increase in the presence of biochar, particularly in the case of legumes, which is consistent with the literature (Liu *et al.*, 2013; Oram *et al.*, 2014). Oram *et al.* (2014) found that biochar increased the competitive ability of red clover against grass and plantain through an increase in K availability. In addition, biochar may specifically enhance biological N_2 fixation in legumes (Rondon *et al.*, 2007; Güereña *et al.*, 2015) and therefore promote growth based on a greater array of mechanisms than crops that do not fix atmosheric N_2, which will also reduce the challenge of crop N deficiency that may be induced by biochar on the short term due to N immobilization in soil (Lehmann *et al.*, 2003).

4.6 Effect of Application Rates and Simultaneous Addition of Other Amendments.

This meta-analysis showed that the addition of biochar alone rendered no effect size on yield regardless of the control used, although its mean effect size when compared to non-amended soils averaged 7% (Bootstrap CI 95%: −0.8−15.7%, n = 62). When compared with the "non-fertilized control", the provision of balanced fertilizer addition with inorganic fertilizers (without biochar) rendered a greater yield effect size than adding biochar without balancing for nutrients (26%; Bootstrap CI: 15-40%; n = 108). Since biochar does not act as an N fertilizer and biochar type and application rates are usually not adjusted to meet crop nutrient needs, this is not a surprising result. Notably, in this same comparison with the "non-fertilized control", when biochar was added along with IF, benefits on crop yield increased to 48% (Bootstrap CI 95%: 30–70%, n = 78), thus rendering a 22% greater increase in yield than the addition of fertilizer alone, yet this difference was not significant. The supplementary benefits provided by biochar when applied along with IF were especially evident in the comparison with the "fertilized control", which resulted in a greater crop yield (an average of 14.5%; Bootstrap CI: 95%: 11-19%, n = 167) (Supplementary information; Table S2) than just IF. Therefore, the overall effect of biochar addition (when supplied with IF) was ≥ 15%, which is in the same order of magnitude as the increase of adding just IF to soils. In both comparisons on the effect of biochar (with and without fertilizer) on crop yield with the two controls considered, a large fraction of the soils had a soil pH ≤ 6.5. This suggests that this increase may be to some extent related to the liming value of biochar in acidic soils (12% increase for pH values ≤ 6.5 compared with the "fertilized control"), yet other benefits (i.e., increased efficiency of fertilizers, better synchronization of nutrient supply, enhanced soil water retention) cannot be disregarded.

When compared with the "non-fertilized control", the meta-analysis also indicated that, for the crops to yield at their optimum potential, N application rates > 100 kg N ha^{-1} were needed (consistent with other meta-analysis where the long-term effect of OA or IF were investigated; Chen *et al.*, 2018). Besides, it should be kept in mind that (i) N in biochar is largely unavailable (Wang *et al.*, 2012b) as it is mostly present as heterocyclic aromatic N (Knicker, 2010), and (ii) the easily mineralizable fraction of organic C in biochar may cause an initial net N immobilization (Bruun *et al.*, 2012; Wang *et al.*, 2012b). Thus, the addition of some form of available N (either organic or inorganic N) along with biochar is recommended.

In general, the application rate of biochar did not have any clear effect on crop yield (Figure 4), whereas application at 5–10 t ha^{-1} rendered greater yields than those applied at 10–20 t ha^{-1} when compared to the "fertilized control". Liu *et al.* (2013), in their meta-analysis, found that crop productivity tended to decrease with increasing biochar application rates, this decrease being significant at application rates > 40 t ha^{-1}. Contrastingly, Biederman & Harpole (2013) observed no relationship between the amount of biochar added and crop yield in their meta-analysis study. Our main dataset only considered the crop yield during the first year of biochar application and it may be possible the benefits observed in the short-term were mostly related to the liming effect of biochar in the soil. Considering an average liming value of 5% $CaCO_3$-equivalence for a cereal biochar (i.e., wheat straw) (Singh *et al.*, 2017), even an application rate of *ca*. 10 t ha^{-1} biochar, equivalent to 500 kg of pure $CaCO_3$, could be sufficient to overcome crop acidity stress in the short term. Therefore, the benefits of biochar application rates above this value might not be apparent. Other agronomic benefits, such as an enhanced resilience of cropping systems against extreme situations (e.g., drought events) might only be evident in specific years for which longer-term field studies would be needed.

4.7 Changes in Crop Effect Sizes Over time.

These comparisons done in a separate meta-analysis included only studies that contained crop yield data over multiple years after a single application of biochar. The meta-analysis rendered opposing results depending on the type of control considered, which was, in the first instance, unexpected. Yet the small number of studies included in the comparison with the "non-fertilizer control" limits the interpretation of the results. In this comparison, the attenuation of crop yield increases after the second year could be explained by an initial dominant effect of biochar associated with its liming potential and direct additions of nutrients contained in the biochar, with these effects decreasing over time, similar to lime or fertilizer additions (Havlin *et al.*, 2005). In contrast, the increase in crop yields relative to the control observed after the second year when both the treatment and the control were fertilized may be explained by the fact that nutrients are retained over time either because of a cumulative effect (Major *et al.*, 2012) or because oxidation takes time to increase cation retention (Cheng *et al.*, 2008). Other meta-analyses have shown either the persistence of benefits for at least two years after the amendment (Liu *et al.*, 2013) or even increases over time (7.0 and 12.3% relative increases in crop yields in the second and fourth season, respectively; Crane-Droesch *et al.*, 2013), but did not distinguish between fertilized and unfertilized fields. A high uncertainty remains about the long-term (>4 years) response of specific soil-crop systems to biochar amendments due to the lack of long-term data.

5. Conclusions

The possibility of separately considering the types of amendment received in both the treatment and the control allowed us to discern the additional crop yield effect from biochar application when applied along with 'business-as-usual' fertilizers. Based on this dataset, in which the short-term effect (1 year) of biochar applications ≤ 20 t ha^{-1} on crop yield were considered, we have found that if the soil received both biochar and inorganic fertilizer the contribution of biochar to the yield increase beyond that of the addition of fertilizer was, on average, ≥ 15%. Part of this increase could be attributed to the short-term liming value of biochar (> 90% were derived from plant residues), especially considering that there was a bias in the results due to the predominance of low-pH soil in the dataset considered (71% of the observations had a soil pH ≤ 6.5), yet other benefits cannot be disregarded (i.e., in soils with small CEC, small OC content, and sandy texture). In fact, the 31% increase in crop yield observed over time (≥ 3 years) in a separate meta-analysis implies that biochar properties other than just its liming value are also playing a role (i.e., an increase in CEC). In relation to the choice of biochar additions, our results suggest that (i) biochars with a large liming value should not be applied to high-pH soils, and (ii) biochar application rates > 10 t ha^{-1} do not contribute to greater crop yield (at least in the short term). Data limitations currently preclude identification of feedstock, production conditions, or climatic conditions without bias. As the response of crop yield to biochar addition was less a result of climatic zones or soil type than fertilizer use, chiefly N additions, the choice of nutrient addition with biochar should be priorities for future research and development regardless of the region.

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Table 1 Treatment and Definition of Categories

Parameters	Grouping	Notes
Crops	Maize	
	Rice	
	Wheat, barley, oat	
	Mixed vegetables	Tomato, broccoli, babocha bok choy, coriander, lettuce, spinach, chilly
	Rapeseed/sunflowers	
	Legumes	Beans, peas, peanuts
	Tuber or bulbs	Potato, beetroot, radish, cassava, garlic
Climate	Tropical or subtropical	Obtained following the Köppen climate classification system
	Mediterranean	
	Continental or humid-temperate	
	Savannah	
Soil texture	Sandy	Sand, loamy sand, sandy loam
	Loam	Sandy clay loam, loam, clay loam, silty clay loam
	Clay	Clay, sandy clay, silty clay
Soil order	Entisol or Inceptisol	Soil Taxonomy (Soil Survey Staff, 2014), except for Paddy soils
	Alfisol or Cambisol	
	Ultisol or Oxisol	

	Paddy soil	
Initial soil pH	≤ 6.5	Soil pH measured in DI water (1:1, 1:2.5, 1:5, 1:10), $CaCl_2$ (1:2, 1:2.5, 1:5), and KCl (1:2, 1:2.5, 1:5) were converted to soil:water = 1:2.5 following Conyers & Davey (1988), Lierop (1981), and Kabala *et al.* (2016). The initial soil pH ranged from 4.2 to 8.5.
	> 6.5	
Initial SOC	≤ 20 g kg^{-1}	When total C was reported in acidic soil, the values were considered as organic C. Initial soil organic C ranged from 3.4–33 g kg^{-1}
	> 20 g kg^{-1}	
Initial soil CEC	≤ 100 $mmol_c$ kg^{-1}	Initial soil CEC ranged from 16–312 $mmol_c$ kg^{-1}
	100–200 $mmol_c$ kg^{-1}	
	> 200 $mmol_c$ kg^{-1}	
Feedstock	Animal and human wastes	Cattle feedlot manure, pig manure compost, cattle dung, poultry litter, farm yard manure
	Cereals and other grasses residues	Maize cobs, rice husk, miscanthus
	Ligneous materials	Straw, wood, walnut shell, oil mallee, peanut hull, coconut shell, bamboo, cassava stem, acacia stem, bark, branches
	Papermill residue	
Pyrolysis highest heating temperature (HHT)	≤ 400 °C	Biochars produced using traditional kiln were allocated in the group of 550–700 °C (http://www.fao.org/docrep/X5328E/x5328e07.htm). HHT classes have been established based on the changes in the chemical structure
	400–550 °C	
	550–700 °C	

	> 700 °C	of biochar as HHT increases (these are described in Keiluweit et al., 2010)
Biochar pH	≤ 9	
	> 9	
Biochar application rate	≤ 5 t ha^{-1} yr^{-1}	Biochar amendment application rates were considered on a dry weight basis and only the rates ≤ 20 t ha^{-1} yr^{-1} were considered
	5–10 t ha^{-1} yr^{-1}	
	10–20 t ha^{-1} yr^{-1}	
N application rate	0 kg ha^{-1} yr^{-1}	
	≤ 100 kg ha^{-1} yr^{-1}	
	100–200 kg ha^{-1} yr^{-1}	
	> 200 kg ha^{-1} yr^{-1}	
Treatments	Biochar	
	Biochar + IF	
	Biochar + OA	
	Biochar + IF + OA	

FIGURE CAPTIONS

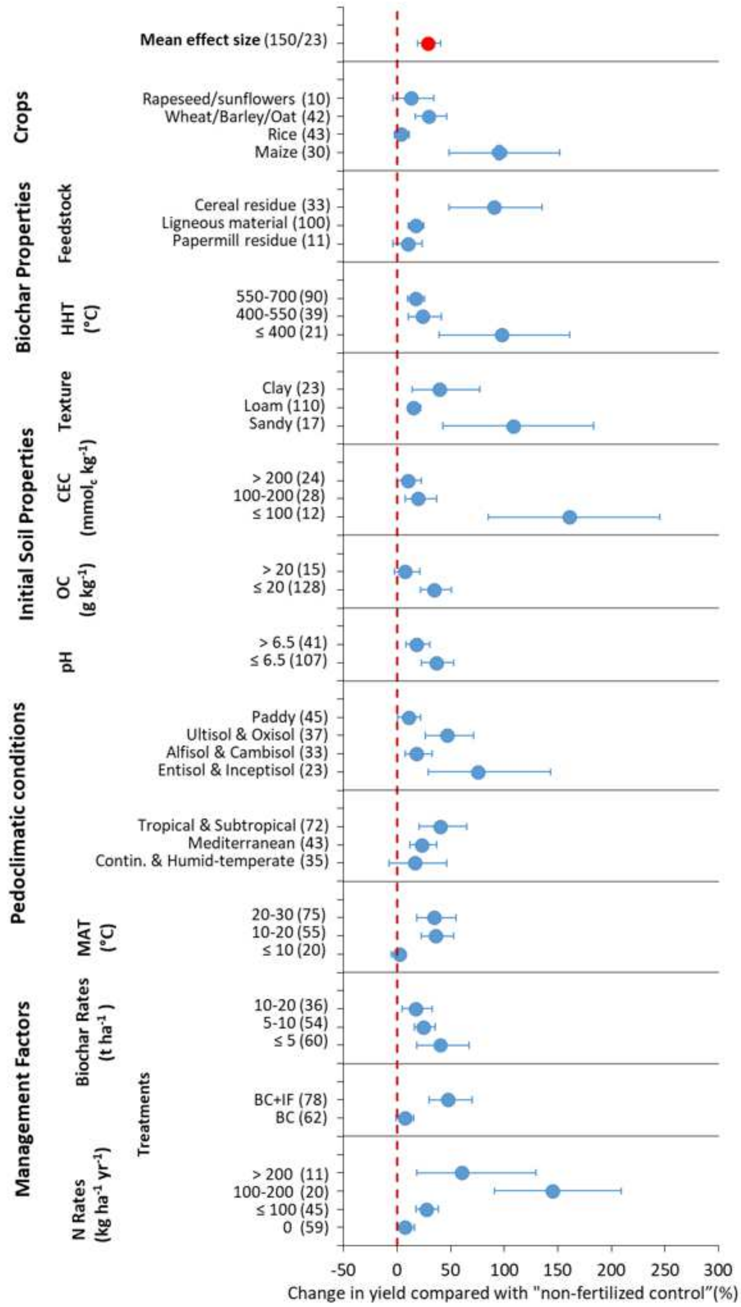
Figure 1 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer (IF) and/or organic amendment (OA)) for each level of the individual categories over the "non-fertilized control". The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The right number within parenthesis for the mean effect size is the number of independent publications from which the data are drawn. The data used to generate this figure is provided in Supplementary Information (Table S2).

Figure 2 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) for each level of the individual categories over the "fertilized control". The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The right number within parenthesis for the mean effect size is the number of independent publications from which the data are drawn. The data used to generate this figure is provided in Supplementary Information (Table S3).

Figure 3 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) over the control (A: "non-fertilized"; B: "fertilized") for soils with different initial soil pH values and application of biochar with different pH values. The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The data used to generate this figure is provided in Supplementary Information (Table S4).

Figure 4 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) at different rates over the control (A: "non-fertilized"; B: "fertilized"). Studies that included biochar application rates > and ≤ 20 t ha^{-1} were considered separately. The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The right number within parenthesis for the mean effect size is the number of independent publications from which the data are drawn. The data used to generate this figure is provided in Supplementary Information (Table S5).

Figure 5 Proportional changes in crop yield caused by biochar additions (with and without the use of inorganic fertilizer and/or organic amendment) at different time intervals since the start of the experiment over the control (A: “non-fertilized”; B: “fertilized”). Only those studies that included crop yield data for several years after a single application of biochar were considered. The red dotted lines represent the overall mean change in crop yield among all studies combined. The numbers in parentheses show the number of pairwise comparisons on which the statistic is based. The right number within parenthesis for the mean effect size is the number of independent publications from which the data are drawn. The data used to generate this figure is provided in Supplementary Information (Table S6).



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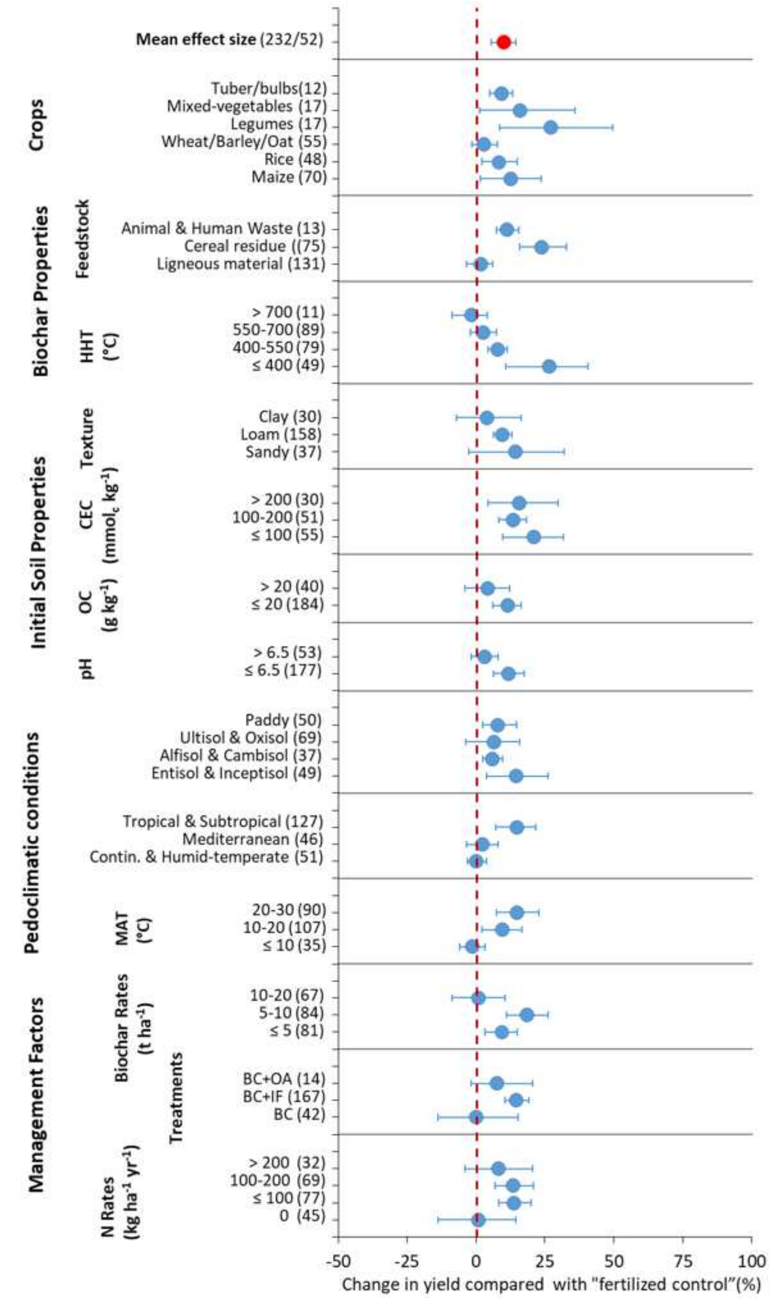

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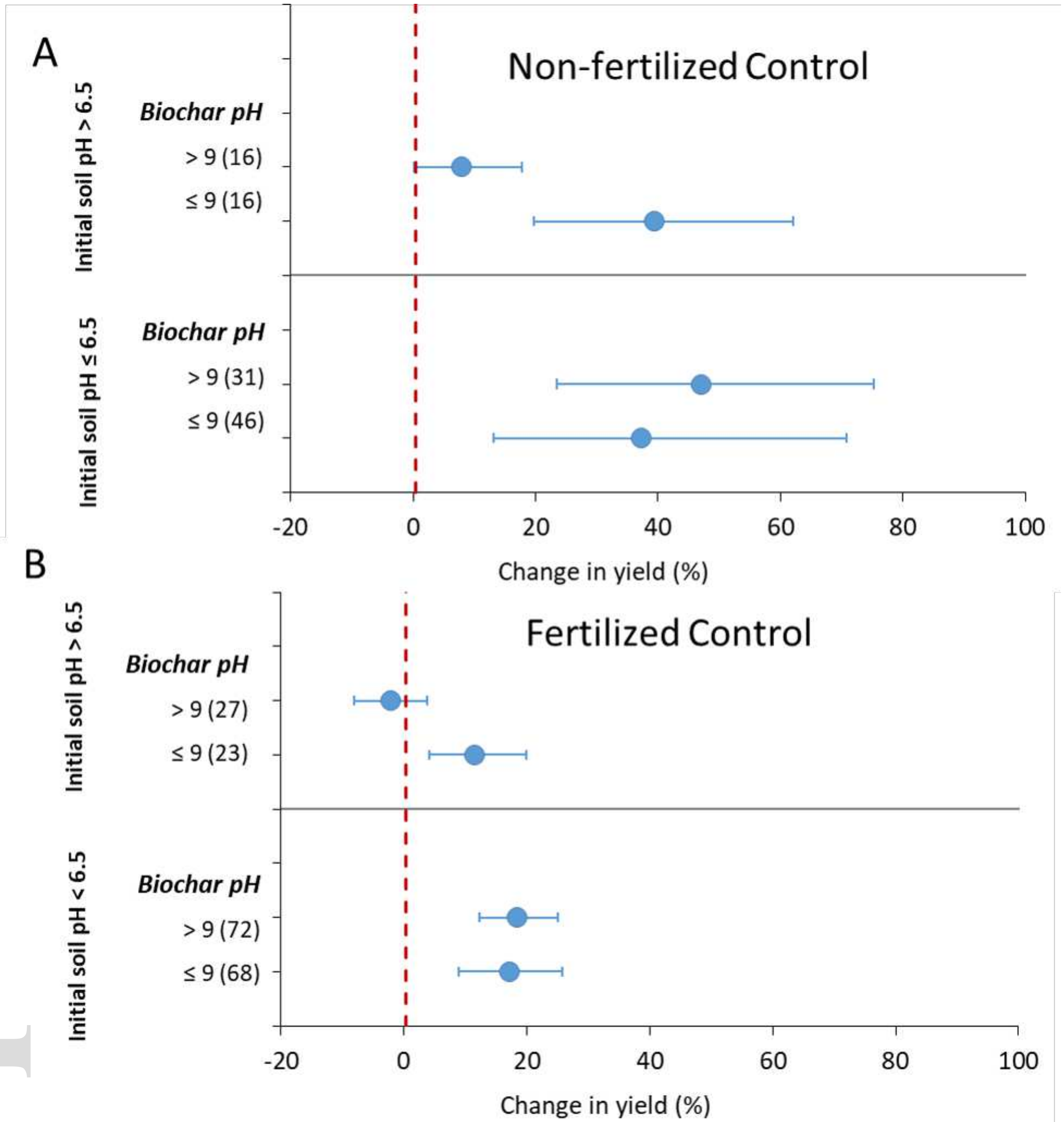

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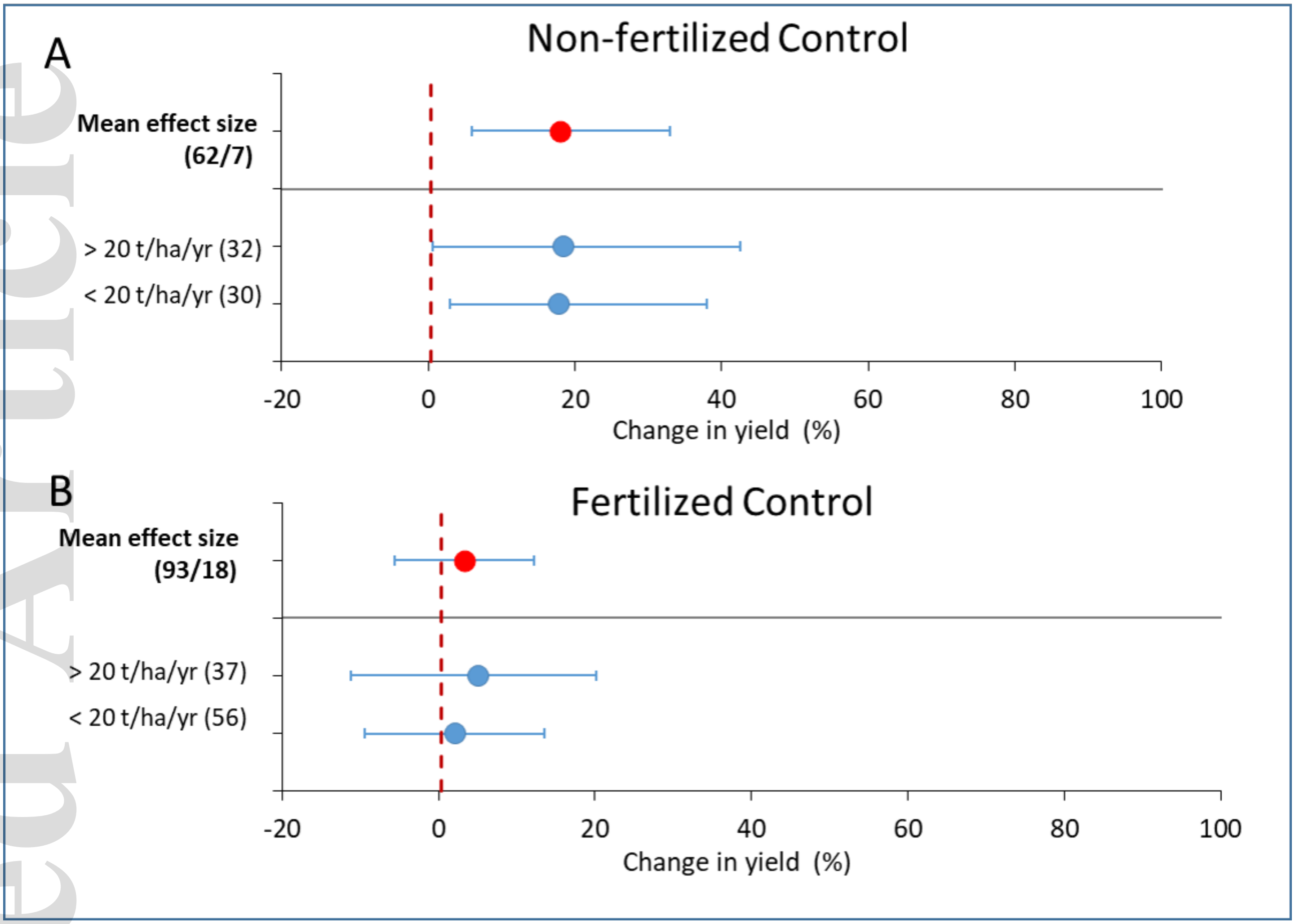

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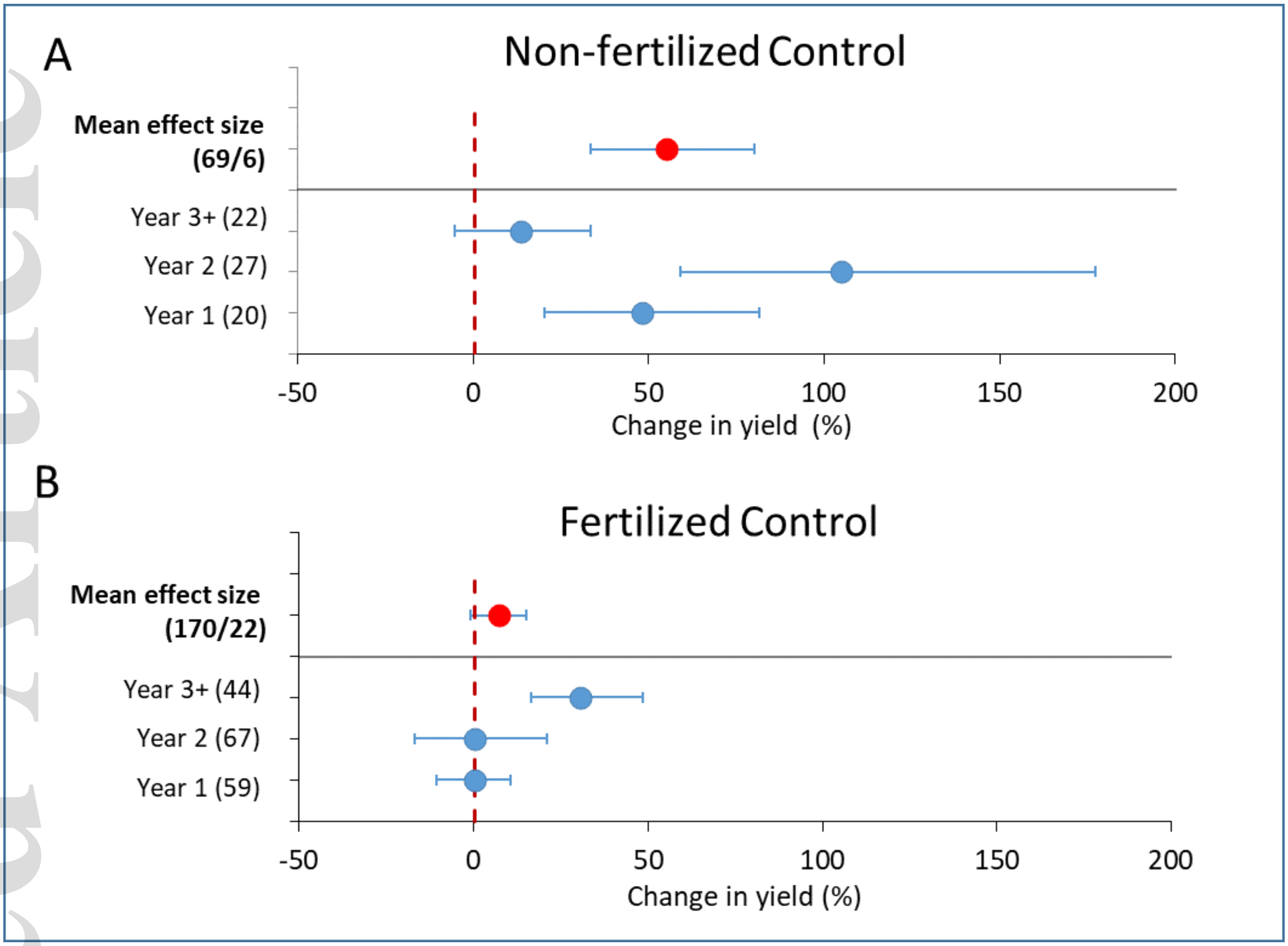

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