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RESEARCH REVIEW

Biochar in agriculture – A systematic review of 26 global meta-analyses

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Abstract

Biochar is obtained by pyrolyzing biomass and is, by definition, applied in a way that avoids its rapid oxidation to CO_2. Its use in agriculture includes animal feeding, manure treatment (e.g. as additive for bedding, composting, storage or anaerobic digestion), fertilizer component or direct soil application. Because the feedstock carbon is photosynthetically fixed CO_2 from the atmosphere, producing and applying biochar is essentially a carbon dioxide removal (CDR) technology, which has a high-technology readiness level. However, for swift implementation of pyrogenic carbon capture and storage (PyCCS), biochar use in agriculture needs to deliver co-benefits, for example, by improving crop yields and ecosystem services and/or by improving climate change resilience by ameliorating key soil properties. Agronomic biochar research is a rapidly evolving field of research moving from less than 100 publications in 2010 to more than 15,000 by the end of 2020. Here, we summarize 26 rigorously selected meta-analyses published since 2016 that investigated a multitude of soil properties and agronomic performance parameters impacted by biochar application, for example, effects on yield, root biomass, water use efficiency, microbial activity, soil organic carbon and greenhouse gas emissions. All 26 meta-analyses show compelling evidence of the overall beneficial effect of biochar for all investigated agronomic parameters. One of the remaining challenges is the standardization of basic biochar analysis, still lacking in many studies. Incomplete biochar characterization increases uncertainty because adverse effects of individual studies included in the meta-analyses might be related to low-quality biochars, which would not qualify for certification and subsequent use (e.g. high content of contaminants, high salinity, incomplete pyrolysis, etc.). In summary, our systematic review suggests that biochar use in agriculture has the potential to combine CDR with significant agronomic and/or environmental co-benefits.

KEYWORDS
anthropogenic dark earth (ADE), biochar-based fertilization, climate change adaptation, greenhouse gas emissions, negative emission technology (NET), pyrogenic carbon capture and storage (PyCCS), soil organic carbon

1 | INTRODUCTION

The agricultural use of biochar as the result of deliberate wood pyrolysis or as a by-product of cooking, has a history of more than 150 years in the Western World (Allen, 1846; Hagemann et al., 2018; Liebig, 1878) or much longer, if its use in animal husbandry is considered (Cato, 1935). Several ancient civilizations have even much older traditions (Frausin et al., 2014; Kern et al., 2019) where the generation of more fertile soils by adding biochar (i.e. charcoal) mixed with other amendments was practiced, for example, in sub-Saharan Africa (Solomon et al., 2016). However, these anthropogenic dark earths (ADEs) were only recognized by scientists over the past 15 years. Their discovery was triggered by biogeochemical research on ADE in Brazil ('Terra Preta do Indio' (Glaser, 2007)), based on the ground-breaking works of Wim Sombroek (Sombroek, 1966). The recognition of such biochar enriched soils concurred with a growing awareness of global warming and the necessity of carbon dioxide removal (CDR), that is, the creation of carbon sinks (C-sink). The term 'biochar' was initially defined as 'charred organic matter [that] is applied to soil in a deliberate manner, with the intent to improve soil properties' (Lehmann & Joseph, 2009). Lately, an extension of the definition of biochar has been discussed, including beneficial material use (e.g. in building or composite materials) that goes beyond soil use but provides equally C-sinks (Bartoli et al., 2020; EBC, 2020; Schmidt, Anca-Couce, et al., 2019).

In the early years of biochar research, very high relative amounts of biochar were applied both in field and pot trials. These were often >10 tons per hectare up to 100 tons (Biederman & Harpole, 2013; Jeffery et al., 2011, 2014; Kammann et al., 2012). The large quantities were mainly due to the fact that Brazilian ADE contain often more than 100 t ha^{-1} biochar-carbon (Glaser, 2007). These C-rich fertile ADE, surrounded by highly weathered soils of low fertility, served as the initial inspiration for early biochar experiments (e.g. Steiner et al., 2008) in the tropics. As biochar research intensified and spread into temperate latitudes, biochar-carbon was discovered in similar dark earth soils as the result of human activity in Northern Germany, Australia and Sub-Saharan Africa (Downie et al., 2011; Solomon et al., 2016; Wiedner & Glaser, 2015; Wiedner et al., 2015). However, it has never been credibly shown that these large amounts of biochar were applied to soils in a single application. The current assumption is that the high biochar-carbon concentrations in Amazonian ADE soils built up over several centuries by repeated application and as part of a recycling system of organic wastes (Glaser & Birk, 2012; Kern et al., 2019). The addition of biochar to organic waste probably minimized nutrient losses, increased biological activity and prevented putrefaction of the organic residues and thus reduced bad odours (Bezerra et al., 2019; Frausin et al., 2014). After incorporation into the soil, those mixes of organic wastes and biochar render the molecular and physical structure of the soil more complex, which apparently lead to the build-up of soil organic carbon (SOC) (Blanco-Canqui et al., 2020; Kammann et al., 2016; Kern et al., 2019; Lehmann et al., 2020). In this context, it is important to note that the dark to black colour of the ADE soil profiles was not derived from the biochar per se but from the substantial accumulation of SOC above that of surrounding weathered, SOC-poor soils (Glaser et al., 2001; Kern et al., 2019; Solomon et al., 2016).

Despite widespread consensus that biochar was always applied with non-pyrogenic organic matter in the traditional models, scientific biochar trials were mostly undertaken with production-fresh, mostly untreated biochar. To avoid experiments with too many varying factors that are hard to normalize, biochar was applied without prior blending with organic and/or mineral nutrients, mixing with biomass and/or inoculating it with an active microbial community. Latest publications and data indicate that biochar is more efficient as an enhancing matrix for fertilizers and microbially active substrates than a pure, mono-constituent amendment (Godlewska et al., 2017; Liang et al., 2021; Sanchez-Monedero et al., 2018; Schmidt et al., 2017a,2017b; Ye et al., 2020) confirming some of the earliest biochar experiments especially from Eastern Asia where organic enhancement and microbial inoculation were already included (Ogawa & Okimori, 2010). However, even if the vast majority of biochar meta-analyses is based on publications that used large amounts of pure, production fresh biochar, compiling the available knowledge condensed in these meta-analyses may help to improve our mechanistic understanding and optimize the application of biochar in agriculture. Here, we address the following key questions: What agronomic and environmental effects may be expected when using a given biochar? Can there be harm when using biochar and if so, how could it be avoided? What settings have the most beneficial effects without negative side effects? The aim of this review is to assist in developing a road map for future beneficial CDR strategies involving biochar use in agriculture, and to shape its future use scenarios to tackle specific agricultural problems.

With more than 17,000 scientific publications on the topic of biochar (Web of Science, April 2021) and the majority of these papers on its agricultural use, a large number of meta-studies (45 in total, see Figure 1) have now been conducted on various topics, from crop yields and root growth, to nutrient dynamics, SOC priming effects, soil biological activity and greenhouse gas (GHG) emissions from soils. Very different biochars, soils and climates around the world are covered.

The present systematic review summarizes the results of 26 meta-analyses published between 2016 and 2020 and meeting pre-defined quality standards. They allow a fair assessment of the overall agronomic effects that can be expected when biochar is used in different agricultural systems and in different regions, which possible side effects must be considered, and to what extent the application may promise environmental and economic benefits.

2 | RESEARCH METHODS

2.1 | Search strategy

We selected biochar-related meta-analyses that were published between 2016 and 2020 but included also several earlier published meta-studies for the overall discussion where necessary. The main reason for focusing on meta-studies published after 2016 is that the newer meta-analyses were able to include a considerably larger number of studies and they often built up on databases from older meta-analyses, which are, thus, indirectly considered in the newest meta-analyses.

We searched the following electronic databases: Scopus and ISI Web of Science Core Collection. To identify the relevant publications, we used the following search terms: 'biochar' AND 'meta-analysis' in 'Article Title, Abstract or Keywords'. We did not include the terms charcoal, pyrogenic carbon, PyC, activated carbon or carbon black, which are different names for essentially the same pyrogenic material as biochar but are generally not used when the pyrolyzed biomass is applied for agricultural purposes. The references cited in, and citing the reviewed studies, were also scanned separately for relevant publications.

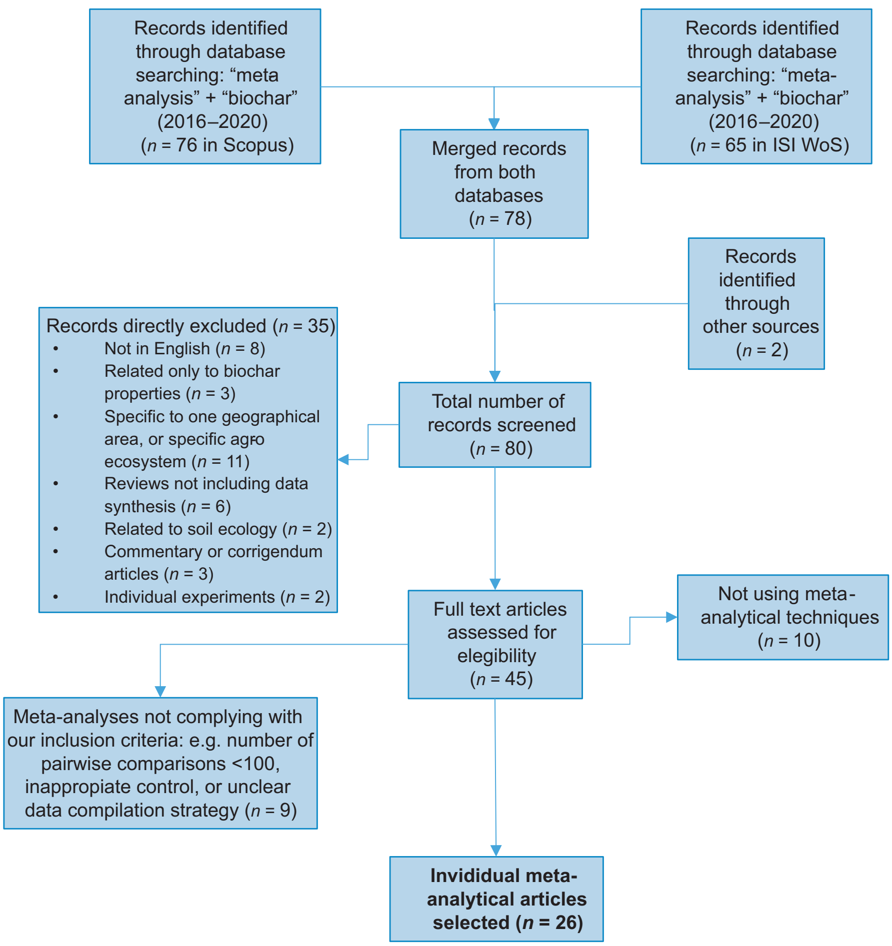

FIGURE 1 Selection path for meta-analyses included in the systematic review

This search strategy resulted in 76 publications in Scopus and 65 in ISI Web of Science (Figure 1). When merged, the results of both databases yielded 78 articles. Two additional articles were found by manual search (He et al., 2020 and Pockarel et al., 2020).

2.2 | Selection of studies

We assessed the titles and abstracts of all retrieved references of relevance to the objective of this review. We excluded studies that (a) were not in English, (b) evaluated only biochar properties, (c) focused on one geographical area or specific agro-ecosystem like paddy rice that are not representative for general agriculture, (d) related to very specific aspects of soil ecology, (e) when reviews did not include data analysis and (f) commentary, corrigendum articles or individual experiments (Figure 1). We included all studies that investigated agronomically relevant effects of biochar soil application and found 45 meta-studies that fulfilled these requirements. From those, we excluded 10 studies that did not use proper meta-analytical tools (Gurevitch et al., 2018) but carried out other statistical methods instead (e.g. paired *t*-tests, analysis of co-variance). Finally, we set up the following quality criteria: (a) a minimum of 100 pairwise comparisons (biochar/control) for the selected parameter; (b) exclusion of studies that used time-series data as independent and (c) in the case of GHG emissions, we excluded studies that did not clearly specify what type of data (cumulative, average or daily fluxes) were collected because this is a critical aspect that can bias the results. Eventually, a total of 26 independent publications, summarizing more than 30 parameters were selected. However, it cannot be excluded that original data points were used by several meta-analyses dedicated to the same parameters (e.g. GHG-emissions). Most publications presented more than one meta-analysis (Table 1). Each of the selected meta-analyses were grouped under 11 topical parameters and are discussed individually in the following sections. Reported results were only discussed as significant when the 95% confidence intervals of effect sizes did not overlap with zero. Several studies that did not meet the above requirements were discussed in the respective sections if they provided complementary data and interpretation to shed light on the underlining mechanisms; however, they were not included in Table 1 and Figures S2a,b.

2.3 | General assessment of the quality of selected meta-analyses.

The implementation of meta-analyses in agricultural sciences is very recent compared with medical or social sciences. Its generalized use, however, is rapidly growing, which can be very useful if they are conducted to a high standard (Philibert et al., 2012).

All meta-studies included in Table 1 and Figure 2 used meta-analytical techniques, that is, they extracted data from individual studies in the form of effect sizes, which were entered into a statistical model with the goal of assessing overall effects and heterogeneity in outcomes (Gurevitch et al., 2018). They also evaluated heterogeneity with random-effects models as generally recommended in agronomic studies (Philibert et al., 2012). The vast majority of studies included the program (and specific packages) they used for the statistical analyses, the weighing methodology and the terms used in the bibliographic search. However, there were other quality measures that were not consistently followed by all studies: (a) the inclusion of detailed quality criteria for the selection of the studies, (b) data harmonization, (c) data availability, (d) analysis of publication bias, (e) consideration of non-independent data and (f) the inclusion of sensitivity analyses. In the following, we further detail the proportion of the selected studies that did or did not follow these quality measures:

1. About 60% of meta-analyses included detailed quality criteria for the study selection. These quality criteria could be for instance that the studies they have include should have a minimum of replicates per treatment, a randomized experimental design, the use of a specific technique for measurements, etc. The inclusion of quality criteria for primary studies in systematic reviews is essential to avoid the effect known as 'garbage-in-garbage-out'. The effect of the differences in inclusion criteria on the results of meta-analyses have been widely discussed in other disciplines (Whittaker, 2010).
2. Equally important, only 56% of the studies gave details about data harmonization (e.g. Gao et al., 2019; Jeffery et al., 2017; Verhoeven et al., 2017; Xiang et al., 2017; Ye et al., 2020). This is very relevant because studies might report relevant data with different units, or measured with different methods. A clear example is the biochar application rate, which many studies provide in % of volume or weight, whereas others as kg per ha or even kg of C per ha. It is highly recommended in such cases to show how data have been harmonized in the common data set that was finally analysed.
3. Although most meta-analyses provided the list of primary studies included for the meta-analysis, only 40% of selected studies made their full data sets available (Borchard et al., 2019; Gao et al., 2019; He et al., 2020; Jeffery et al., 2017; Ji et al., 2018; Peng et al., 2018; Verhoeven et al., 2017; Zhang et al., 2018, 2019). This is a moderately high percentage compared, for instance,

TABLE 1 Mean effect sizes (% change), 95% confidence intervals and number of direct pairwise comparisons in the 26 selected meta-analyses. Results represent grand means and, since all meta-analyses showed high heterogeneity, we recommend looking up the original studies for specific details. Three of the selected meta-analyses (marked with *) did not use the response ratio as the effect size (Cong et al., 2018; Jeffery et al., 2016 and Li et al., 2020) and therefore their results cannot be represented as % change

Authors	Main parameter summarized	Mean effect size (% change)	95% CI (±)	# Comparisons - (independent studies)	Comments
Yield					
Dai et al., 2020	Plant productivity	16	1.3	1254 (153)	Including total biomass, grain yield, aboveground biomass, root biomass
Jeffery et al., 2017	Crop yield	13	2	1125 (109)	25% yield increase in tropical agriculture / no yield effect in temperate latitudes
Ye et al., 2020	Crop yield (biochar +fertilizer)	10	4.6	232 (52)	Biochar +fertilizer treatments compared to fertilizer only
Stimulation of root growth and photosynthetic performance					
He et al., 2020	Photosinthetic rate	27	5	322	The rate at which a plant captures radiant energy and fixes it in organic carbon compounds
He et al., 2020	Stomatal conductance	20	4	261	
He et al., 2020	Transpiration rate	27	5	214	Rate of evaporation of water via plant leaves
He et al., 2020	Chlorophyll concentration	16	4	163	
Xiang et al., 2017	Root biomass	32	5	627	
Xiang et al., 2017	Root length	52	10	238	
Xiang et al., 2017	Number of root nodules	25	10	113	
Xiang et al., 2017	Root fungal colonization	−4	7	105	
Microbial biomass and enzymatic activity					
Li et al., 2020	Microbial biomass PLFA*	*1*	*0.25*	336	'Hedges g' used as effect size. Consult the original source for the correct interpreation of results
Pockarel et al., 2020	C enzymes	−5	11	162(43)	
Pockarel et al., 2020	N enzymes	23	16	121(36)	
Pockarel et al., 2020	P enzymes	3	11	161 (44)	
Pockarel et al., 2020	Microbial biomass C	22	10	108(30)	
Pockarel et al., 2020	Dehydrogenase	19	18	108 (26)	
Zhang et al., 2018	TOTAL PLFA	8	5	147	
Zhang et al., 2018	Bacteria	20	5	154	
Zhang et al., 2018	Fungi	19	4	242	
Zhang et al., 2018	Actinomycetes	9	4	197	
Zhang et al., 2018	Gram-positive bacteria	11	4	189	
Zhang et al., 2018	Gram-negative bacteria	13	4	192	
Zhang et al., 2018	Fungi/bacteria ratio	6	5	154	
Zhang et al., 2019	All enzymes' activity	5	2	401	
Zhang et al., 2019	C-cycling enzyme activity	−6	3	170	

(Continues)

TABLE 1 (Continued)

Authors	Main parameter summarized	Mean effect size (% change)	95% CI (±)	# Comparisons - (independent studies)	Comments
Zhang et al., 2019	N-cycling enzyme activity	14	4	155	
Zhou et al., 2017	Soil microbial carbon	26	4	413	
Zhou et al., 2017	Aoil microbial nitrogen	22	11	106	
Zhou et al., 2017	Metabolic quotient (qCO2)	−13	4	151	Respiration to biomass ratio; qCO2 often declines with increasing pH and amounts of microbial biomass
Plant-available water and bulk density					
Gao et al., 2020	Water use efficiency	20	3	284	Combines plant and leaf water use efficiency
Gao et al., 2020	Plant water use efficiency	19	3	147	
Gao et al., 2020	Leaf water use efficiency	20	6	137	
Omondi et al., 2016	Bulk density	−8	1	463	Bulk density and porosity of soil following biochar application depend mainly on milling of biochar
Omondi et al., 2016	Porosity	8	7	128	
Omondi et al., 2016	Available water content	15	5	274	
Soil organic matter (SOM) increase or the effect of biochar on priming of existing soil carbon					
Bai et al., 2019	Soil organic carbon	39	6	222	Most studies include biochar-C in the SOC measurement here, more important, however, is the SOC dynamic excluding the biochar-C fraction
Liu et al., 2016	Soil organic carbon	52	2	148	
Liu et al., 2016	Soil respiration	3	0.2	167	
Wang, Lee, et al., 2016	Priming of soil organic carbon	−4	4.3	116	Including studies with a stable isotope labelling but without plant-C input
Plant-available phosphorus and mineral nitrogen species					
Gao et al., 2019	Plant-available P	45	5	537	
Gao et al., 2019	NH4+ in soil	−11	5	375	Probably an artefact as the analytical extraction methods for Nmin-species were not adapted to biochar and the missing Nmin fraction is likely captured by the biochar
Gao et al., 2019	NO3- in soil	−11	4	301	
Liu et al., 2018	Plant N-uptake	11	5	340	
Liu et al., 2018	NH4+ in soil	−6	4	331	Probably an artefact as the analytical extraction methods for Nmin species were not adapted to biochar and the missing Nmin fraction is likely captured by the biochar
Liu et al., 2018	NO3- in soil	−12	3	350	
Nguyen et al., 2017	NH4+ in soil	−10	2	889	
Nguyen et al., 2017	NO3- in soil	−11	2	927	

(Continues)

TABLE 1 (Continued)

Authors	Main parameter summarized	Mean effect size (% change)	95% CI (±)	# Comparisons - (independent studies)	Comments
Reduced uptake of heavy metals from contaminated soils					
Chen et al., 2018	Cd in plants	−38	3	505	
Chen et al., 2018	Pb in plants	−39	5	292	
Chen et al., 2018	Cu in plants	−24	4	237	
Chen et al., 2018	Zn in plants	−16	4	266	
Peng et al., 2018	Zn in plants	−20	8	241	Pot studies only
Peng et al., 2018	Cd in plants	−30	4	490	
Peng et al., 2018	As in plants	−19	28	155	
Peng et al., 2018	Ni in plants	−36	6	137	
Peng et al., 2018	Cu in plants	−26	5	193	
Peng et al., 2018	Pb in plants	−41	5	284	
Change of methane fluxes					
Cong et al., 2018	CH4 emissions*	*−0.02*	*0.13*	app. 150	Raw mean differences are used as effect size. Consult the original source for the correct interpreation of results
Jeffery et al., 2016	CH4 emissions*	*0.2*	*0.3*	193	Hedges d' as effect size. Consult the original source for the correct interpreation of results
Ji et al., 2018	CH4 emissions	−61	19	160	
Reduction of N2O emissions, NH3 volatilization and nitrate leaching					
Borchard et al., 2019	N2O emissions	−38	5	435	
Borchard et al., 2019	NO3- leaching	−12	12	120	
Borchard et al., 2019	NO3- in soil	−5	5	146	Probably an artefact as the analytical extraction methods for NO3 were not adapted to biochar
Liu et al., 2018	N2O emissions	−32.3	5	468	No effect in field but only in pot trials
Liu et al., 2018	Total N leaching	−26.6	5	156	
Verhoeven et al., 2017	N2O emissions	−12.4	5	122	Only field studies
Sha et al., 2019	Ammonia volatilization	0.9	13	141	

with the 31% found in plant ecology (Koricheva & Gurevitch, 2014). Data availability (either deposited in publicly available repositories or presented as supplementary information) is nowadays considered essential for transparency and reproducibility. Many high-ranking journals require the publication of the data sets to accept a meta-analysis for publication.

4. Publication bias, that is, the over-representation of statistically significant results in the published literature, can distort the results of a meta-analysis. Several methods have been developed to take the possibility of a publication bias into account. About 72% of the selected meta-analyses included methods for testing publication bias (e.g. funnel plots, fail-safe numbers) (Lin & Chu, 2018).
5. Many pairwise observations in a meta-analysis can be non-independent, for example, because they share the same control in a field study, or they might represent data points from a time series. Only a few number of studies took into account or even mentioned the possibility of non-independence in their data sets (Cong et al., 2018; Jeffery et al., 2017; Peng et al., 2018; Verhoeven et al., 2017). The selection of criteria for non-independence was found to be the most important factor leading to different outcomes in meta-analyses (Hungate et al., 2009).

6. Finally, only a very limited number of studies (<20%) included any type of sensitivity analysis (Liu et al., 2016; Zhang et al., 2018), which are very relevant to determine the robustness of meta-analytical results.

To summarize, all selected meta-analysis followed several of the mentioned quality criteria and, in spite of their potential limitations, they can be considered reliable, noting that a certain degree of precaution is always recommended to avoid over-interpretation.

2.4 | Data extraction

Mean effect sizes, 95% confidence intervals and number of pairwise comparisons were extracted from the 26 selected meta-analyses. Data were directly extracted from the text or tables when available. Otherwise, WebPlotDigitizer 4.4 (https://automeris.io/WebPlotDigitizer/) was used to extract data from the figures. The vast majority of meta-analyses used the response ratio (RR) as effect size:

$$\mathrm{RR} = \ln\left(X_T/X_C\right),$$

where X_T represents the mean of the treatment and X_C the mean of the control. In most cases, the effect sizes were directly expressed as % change. When data were reported as RR, the following equation was used to convert it to % change:

$$\%\,(\mathrm{RR}) = \left[\exp\left(\mathrm{RR}\right) - 1\right] \times 100\,\%.$$

The RR, although advantageous because it is very intuitive and can be directly translated to % change, is problematic when there are negative values in the data set. For this reason, some studies chose a different effect size metric, such as the differences between means or the Hedge's d (Cong et al., 2018; Jeffery et al., 2016). These studies could not be directly compared with other studies included in Table 1, but their results are reported as well.

3 | RESULTS AND DISCUSSION

3.1 | Plant productivity

Increasing crop and/or biomass yield is often considered as the most important goal of biochar application. Jeffery et al. (2017) gathered an outstanding database comprising 1125 comparisons from 109 independent studies and reported a significantly increased crop yield of 13% after biochar application. They found a higher effect in acidic soils (e.g. 40% increase for soils with pH <5) compared with neutral or alkaline soils where no significant effects could be found. However, this meta-analysis focuses on biochar as the only amendment and did not include treatments where biochar was applied in combination with mineral or organic fertilizers and compared with fertilized controls.

The largest meta-analysis to date of biochar effects on crop yield evaluated 1254 paired comparisons from 153 scientific articles published until November 2017 (Dai et al., 2020). However, the inclusion quality criteria are not clear, and the data set is not public. Unfortunately, this study did not distinguish between biochar applications with and without fertilizer. Regardless of the biochar quality and soil conditions, the authors calculated a mean yield increase of 16% though the variability of the data was very high, ranging from −32% to +974%. Here, the yield increases were significantly positive both for alkaline and for acidic soils though higher for the latter. The authors examined this variability in more detail and plotted it as a function of specific biochar and soil properties. Their analysis indicates that in alkaline soils, the biochar-induced changes in SOC content, electrical conductivity, C/N ratio and cation exchange capacity (CEC) were the main causes of yield enhancement (Liu et al., 2019; Zheng et al., 2017). Regarding biochar properties, the pH of the biochar (pH 7–8), its ash content (>25%), its bulk density (<0.3 kg/l) and its C/N ratio were the most critical factors for the achieved yield increases. Further results from Dai et al. (2020) indicate that biochars made from crop residues, straw, manure and sewage sludge had more pronounced yield effects than biochars from woody biomass when not blended with fertilizers. These results contrast with the trend in Europe, where biochar is produced mainly from wood to achieve high carbon and low ash contents. The biochars identified as most promising by Dai and colleagues were consistently rather ash rich. Biochar application achieved the best results on yield when applied to sandy, acidic (pH <6) soils with low CEC and higher nitrogen contents.

In a meta-analysis of high technical quality, Ye et al. (2020) evaluated 56 publications with 264 direct comparisons on sole and combined effects of biochars and fertilizers on crop yield across different soils and climates. Importantly, the authors clearly distinguished between studies that used biochar with and without fertilizer, matching them to respective fertilizer (or no fertilizer) controls. They demonstrated that biochar is not only an amendment for weathered tropical soils but can, in combination with fertilizers, also result in significant crop yield increases in temperate climates. The application of biochar and fertilizer in combination resulted in an

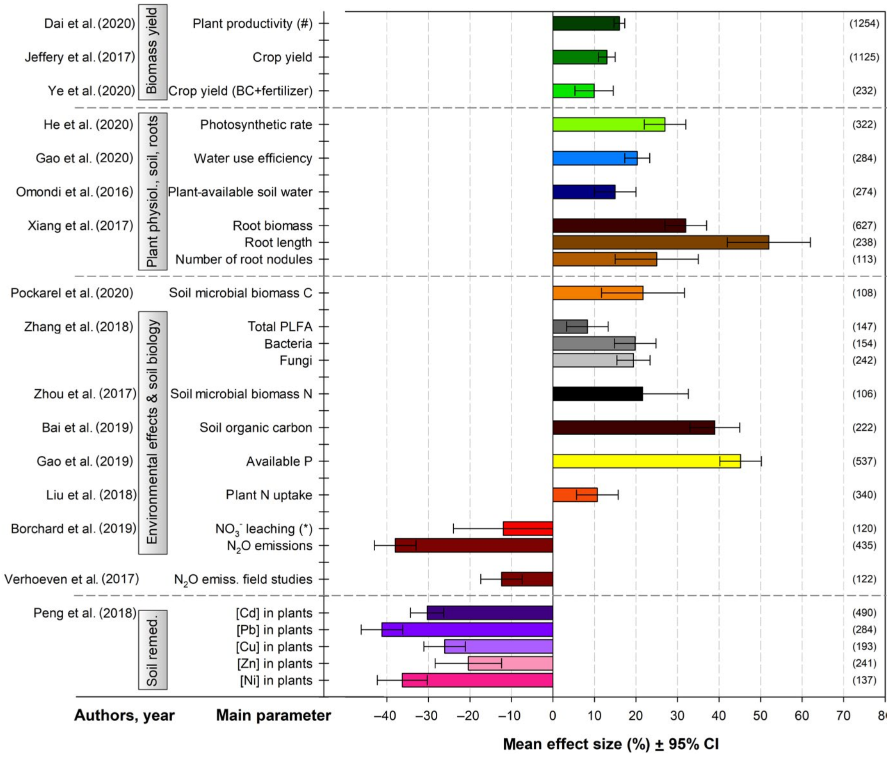

FIGURE 2 Selected parameters with highest agronomic relevance that were investigated in the 26 reviewed meta-analyses. The mean overall effect size (% change) and 95% confidence intervals are given as reported in the original studies. The numbers in parentheses indicate the number of pairwise comparisons used for that specific parameter

average yield increase of 15% compared with fertilization with the same amount of nutrients but without biochar. The biochar application rates were well below 10 t ha^{-1}. Remarkably, the highest yield increases were not achieved with biochars from wood but straw and other rather lignin-poor, mineral-rich biomasses, which is in good agreement with the results of Dai et al. (2020) discussed above. However, no impact of biochar on yields was found for regions with mean annual temperatures lower than 10°C.

To summarize, all recent meta-studies about yield effects conclude that the use of biochar in soils induced an overall higher yield (Figure 2) even if this was not the case in every soil and not with every biochar. As a way forward, we suggest to systematically investigate the following questions to further optimize biochar-based fertilization:

1. Type of biochar (biomass feedstock, pyrolysis conditions, particle size) and possible post-pyrolysis treatment (biological treatments such as lactic fermentation or composting, chemical treatments such as acidification, etc.).
2. Mode of mixing of biochar and fertilizer (separate application, mixing of biochar with liquid fertilizer, mixing of biochar with a solid, chemical formulation of the blended fertilizer, etc.)
3. Optimal application method (homogeneous spreading, strip application, injection, micronized biochar particles via drip irrigation, etc.).

Biochars may contain and release relevant amounts of macro- and micronutrients when produced from mineral-rich feedstock, especially from manures and biosolids (Ippolito et al., 2020). However, total and available nutrient concentrations in biochar from vegetal feedstock are usually too small to fully replace conventional fertilizers. Therefore, biochar is generally not considered a fertilizer and should be combined with organic or mineral fertilization to improve plant nutrition. This may encompass the formulation of granular biochar-containing organic or mineral fertilizer products as part of future CDR strategies.

Organic nutrient-rich solutions and suspensions such as cattle urine (Schmidt et al., 2015), biogas slurry (Glaser et al., 2014), press water from tofu production (Barber et al., 2018), compost tea (Edenborn et al., 2018) or commercial liquid fertilizers are suitable for nutrient enhancement of biochar. Mineral NPK fertilizers have also been shown to be effective solutions for the preparation of biochar-based fertilizers (Dietrich et al., 2020; Liu et al., 2019; Omara et al., 2020; Shi et al., 2020; Ye et al., 2020; Yu et al., 2018). Thus, biochar can act as a carrier matrix for nutrients to reduce leaching (Borchard et al., 2019). Fertilizers are either loaded in liquid form into the pore structure of the biochar or mixed in solid state, for example, by granulation or pelleting. Alternatively, they are co-applied. To this end, biochar can be incorporated into the topsoil while fertilizers are applied to the surface and would slowly percolate by rainwater into the biochar containing soil layers. Biochar apparently improves the microbially controlled root uptake of nutrients as well as electric charge neutralization between roots and soil (Chew et al., 2020; Joseph et al., 2013, 2015, 2017; Schmidt et al., 2017a,2017b).

With specifically developed biochar-based fertilizers, it could be expected that, depending on the cultivation system, higher yield effects than the average yield increase reported by the meta-analyses could be achieved in the future. Conversely, in already optimized high-yield systems such as arable farming on fertile soils with sufficient precipitation combined with optimized fertilization or special crops grown with fertigation, further yield increases are more difficult to achieve. However, even in these systems, lower increases would be economically relevant; or the same yields may be achieved with less input and at lower environmental costs.

3.2 | Stimulation of root growth and photosynthetic performance

Xiang et al., (2017) conducted a comprehensive meta-analysis on the effects of biochar on the growth and morphology of roots assessed by various parameters, including 136 published studies with 2108 paired records. Biochar amendment increased plant root biomass by an average of 32% and root surface area and specific root length by 39% and 52%, respectively, as well as the number of root tips (17%) and the number of N_2-fixing nodules (25%). These changes in the presence of biochar were more pronounced in annual crops than in perennial (woody perennial) crops and were significantly higher in legumes than in non-legumes. On average, root N concentration was not altered, but root P concentration increased by 20%. Evaluation of the effects of biochar showed that pyrolysis conditions, especially pyrolysis temperature and pyrolysis intensity (heat transfer, residence time, mineral catalysts, highest treatment temperature), played a more significant role than the different feedstocks used for biochar. Biochars made at higher temperatures are generally more alkaline, have lower nutrient availability, and present higher specific surface area, water-holding capacity and electric conductivity, which are all characteristics that may explain increased root growth. Overall, this meta-analysis indicates that biochar increases the nutrient appropriation capacity, especially for phosphorus, by promoting root growth (especially root length and branching).

As the formation of SOM is mainly dependent on plant roots, their exudates and fine root turnover (Kätterer et al., 2011; Lehmann et al., 2020; Rasse et al., 2005), biochar-induced promotion of root growth is a highly relevant effect with regard to soil fertility, crop resilience, and climate change mitigation. The reported increases of root biomass, root volume, root surface area, root density, and root length are likely to affect the nutrient and water uptake of plants positively, which indirectly increases photosynthetic C-acquisition and can, therefore, improve overall plant growth and/or plant resilience (Bruun et al., 2014; Makoto et al., 2010). Enhanced root growth and photosynthetic performance do, however, not necessarily lead to equally higher crop yields because the increased plantal energy throughput might primarily be used for higher root growth and root exudation for nutrient acquisition and stimulation soil microbiota.

He et al., (2020) investigated plant physiological parameters such as photosynthetic rate, stomatal conductance and water use efficiency (WUE) at the leaf level via 347 data sets from 74 publications. Biochar application increased the above-mentioned parameters between 16% and 27%. Remarkably, biochar application showed a significantly higher effect in C3 plants (32%) such as wheat, rice and soybean than C4 plants (7%) such as maize, sugarcane, miscanthus and millet. The RR of the photosynthetic rates to biochar amendment was significantly correlated with that of the resulting total, shoot and root biomass, respectively, which was again stronger in C3. This effect might be explained by the fact that C4 plants are usually more heat and water stress-resistant so that the supposed biochar effect on remedying nutrient or drought stresses was probably of less importance.

3.3 | The use of biochar for tree cultures

No meta-analyses have been published after 2016 on the effect of biochar on tree growth. A study by Thomas and Gale (2015) examined the literature on how forest trees responded to biochar's soil amendment and summarized 17 scientific publications covering 36 tree species with trials both in nurseries and adult trees. They reported a mean increase in tree growth of 41% in the treatments with biochar, compared with the control without biochar. Growth increases were particularly pronounced at early growth stages, higher in tropical than temperate climates and higher in deciduous trees than conifers, but significant for all tree species in all climates.

It should be noted that biochar for tree treatments (also in urban tree restauration activities) is usually deliberately applied in the root zone, usually by precise manual application. When planting a tree, the biochar substrate is then added to the planting hole, and for already established trees, it is applied either in the topsoil directly around the tree or in holes or furrows around the radius of the tree canopy. This application method is similar to that recommended for biochar-based fertilization also in field crops (Farrar et al., 2019; Schmidt et al., 2017a,2017b) where the use of low biochar doses (<2 t ha^{-1}) achieved significant yield increases. Because agroforestry and reforestation approaches are increasingly discussed in terms of CDR-delivering land-use change approaches (Cardinael et al., 2017), more studies as well as a first in-depth meta-study on tree planting and establishment with biochar are clearly desirable.

3.4 | Microbial biomass, enzymatic activity and N_2 fixation performance of legumes using pure biochar

Liu et al. (2016) showed that biochar increased soil microbial biomass carbon (MBC), especially in field studies where biochar was applied with fertilizer. They included 80 pairwise comparisons for MBC and found an average increase of 36%. In a meta-study including 413 direct comparisons, the increase in MBC and microbial biomass N (MBN) due to biochar were 25% and 22%, respectively (Zhou et al., 2017). However, significant increases of microbial biomass were only observed on acidic and neutral soils, but not on alkaline ones. In a meta-analysis including 336 direct comparisons Li et al. (2020) found that biochar increased microbial biomass based on phospholipid fatty acid analysis and had variable effects on microbial diversity.

These results are consistent with another meta-analysis that included 108 direct comparisons from 30 publications, where biochar increased soil MBC by an average of 22% (Pokharel et al., 2020). This study focused mainly on soil enzymatic activities and reported an increase in the activity of extracellular enzymes such as urease, phosphatase and dehydrogenase by 23%, 25%, and 20%, respectively. However, a decrease in β-glucosidase, acid phosphatase and phenol oxidase, by −7%, −6% and −13% was also found, respectively, although it was not significant. The greatest effects for N-acquisition enzymes (acetyl-glucosaminidase, leucine amino peptidase and urease) were obtained in low-SOC soils (C < 2%, TN <0.2%) and finely textured soils. These results confirm data assessed by Zhang et al. (2019) on soil carbon, nitrogen, and phosphorus hydrolytic enzymes based on 401 paired comparisons from 43 studies. While the N and P cycling soil enzyme activity (SEA) increased by 14 and 11%, respectively, indicating the stimulation of plant nutrient cycling, the C-cycling SEA decreased by 6%, tentatively indicating reduced SOC turnover. While nutrient-rich, low-temperature biochars stimulated the N and P cycling SEAs, the C-cycling SEA was more suppressed by nutrient-poor, high-temperature biochars confirming that there is no one best biochar for all purposes but differently designed biochars for more or less clearly designed tasks.

Zhang et al. (2018) scanned 265 comparisons of 49 publications for specific microbial effects of different types of biochars in different soils. Across all studies, biochar addition significantly increased the abundance of soil microorganisms (total PLFA), bacteria, fungi, actinomycetes, G+ and G- bacteria by 8%, 20%, 19%, 9%, 11%, and 13%, respectively. The application of biochar in acidic soils and soils with low SOC led to the strongest shifts in the fungi-to-bacteria ratio (+38%). Increased fungi-to-bacteria ratios indicate that carbon decomposition and fungal-mediated N mineralization led to more efficient plant nutrient uptake and plant growth promotion (Luo et al., 2017).

A study on changes in the N cycle (208 studies) as a result of biochar applications (Liu et al., 2018) evaluated a subset of four studies with 25 comparisons regarding the effects of biochar on the stimulation of nitrogen fixation in legumes. Although the data set was rather limited and the meta-analysis did not meet our selection criteria, it is worth noting that the authors found a 63% increase in biological N fixation that was explained by the fact that microorganisms (especially rhizobia) were stimulated, soil pH increased, nutrient supply including P, K, Mo and B was improved, and hence root nodulation was stimulated. More research is needed in this particular area, where the few studies to date show promising results.

3.5 | Plant available soil water and bulk density

Biochar is frequently suggested as an amendment to improve the water-holding capacity of soils and eventually plant available soil water. The highly porous material presenting pore volumes of up to 5 cm^3 g^{-1} (Sigmund et al., 2017) can absorb within the pore structure and between particles significant amounts of water and dissolved nutrients (Conte & Schmidt, 2017). However, to achieve significant effects on soil water availability, large amounts of biochar (>10 t ha^{-1}) would have to be applied.

A meta-analysis by Omondi et al. (2016) found that, on average, soil bulk density significantly decreased by 8% after biochar amendment. Soil porosity significantly and aggregate stability increased both by 8%, available water-holding capacity by 15%, and saturated hydraulic conductivity by 25%. However, the effects are highest with biochar application amounts above 80 t ha^{-1} and low to insignificant at less than 20 t ha^{-1}.

More recently, the meta-analysis by Gao et al. (2020), using 43 studies with 284 pairwise comparisons, found a significant increase in plant WUE of 19% on average and leaf-WUE of 20%. Plant-WUE is defined as the amount of biomass accumulated per total amount of water used (Gao et al., 2020; Pazzagli et al., 2016), while leaf-WUE is defined as water loss per net CO_2-uptake at the leaf (or canopy) level (Gao et al., 2020; Paneque et al., 2016). However, the authors found very high variability in WUE responses, ranging from −36 to +313% which was due to several different factors such as pH, C and K content of the biochar, and application rate (<20 t ha^{-1}). However, the individual data sets were too small and not standardized enough to identify the impact of these different parameters according to the authors.

A meta-study by Razzaghi et al. (2020) was devoted to biochar's effect on the change in bulk density of various soils and on the increase in plant-available water. The mean value of the resulting decrease in soil bulk density across all experiments was 9% and was of the same order of magnitude for all soils and biochar types. With respect to plant available water, however, the results for the various soil types differed considerably. In coarse-textured soils, available water increased by 47%, in medium-textured soils by 9% but in fine-textured soils, biochar had no significant effect. Thus, an agronomically positive impact on water availability was mainly seen in coarse-textured soils and only achieved with very high application rates of 0.27–10% biochar in dry soil. This effect is also used when planting urban trees in intentionally coarse-textured substrates with high concentration of biochar designed to ensure the drainage of rainwater collected on the surface (Embren, 2016). Overall, it should be noted that the water-holding capacity of biochar can vary from less than 50% of its dry weight to more than 500%, depending on the bulk weight, pore structure and surface chemistry (unpublished data, data of EBC certificate analyses, Ithaka Institute), which, along with soil structure and aggregation, mainly determines the water-holding capacity of soils containing biochar.

Another data synthesis study of biochar effects on soil water dynamics was undertaken by Edeh et al. (2020). They found that biochar improved all investigated soil water properties such as available water content (+28.5%; 107 data sets), field capacity (+20.4%; 94 data sets), permanent wilting point (+16.7%; 75 data sets), total porosity (+9.1%; 36 data sets), saturated hydraulic conductivity (−38.7%; 61 data sets) and bulk density (+0.8%; 131 data sets) regardless of the soil type. However, again, the overall effects were dominated by studies that applied more than 30 t ha^{-1}, effects were considerable smaller for lower application rates, except for bulk density. They concluded that particle size, specific surface area and porosity of biochar are the main parameters influencing soil water dynamics. To achieve optimum water relations in sandy soils, biochar with a small particle size (<2 mm) and high specific surface area and porosity are recommended by the authors, while in clayey soils, biochars with larger particle sizes and with high specific surface area are more advantageous.

Although biochar can significantly increase the water-holding capacity of soils and the WUE of plants, the overall agronomic effect must be considered relatively low, especially at low application rates of 0.5–2 tons per hectare and year in arable farming. However, with concentrated root-zone application, higher water availability may be provided to the roots and during the early stages of plant growth when the plants are still especially vulnerable to drought and other stresses. With higher moisture in the root zone, the capacity of the capillary pump (Barghi, 2018), which transports water via capillary principles from deeper soil layers to the humid root zone, can be improved. Also, intensive horticulture and special applications may allow higher application rates so that the benefits regarding water availability can be realized.

3.6 | Biochar induced soil organic matter increase, soil organic carbon–priming, and C-sink

The application of biochar to agricultural soils has been discussed since the beginning of the millennium as a carbon sequestration method (Laird, 2008; Lehmann et al., 2006; Woolf et al., 2010). As biochar applied to soil resists degradation, it can be assumed that most of the pyrolytically transformed carbon persists in the soil for several centuries (Lehmann et al., 2015; Zimmerman & Gao, 2013) and represents, thus, a carbon sink (Schmidt, Anca-Couce, et al., 2019; Werner et al., 2018). It was calculated with two different methods that 13.5, respectively, 13.7% of the global SOC is in fact natural pyrogenic carbon (Leifeld et al., 2018; Reisser et al., 2016). There is strong scientific consensus that the mean residence time (MRT) of biochar carbon in soil is higher than that of all other organic carbon compounds (Coppola et al., 2018; Wang et al., 2016a,2016b). Nonetheless, a very slow degradation of biochar does occur in soils and must be included into any carbon accounting system that covers the time scales of generations.

Due to the absence of long-term experiences (>100 years), knowledge about biochar degradation is limited and either based on natural pyrogenic carbon turnover (Hammes et al., 2008) or on modelling of data from shorter term experiments. Using 128 observations of biochar-derived CO_2 from 24 studies with stable (^{13}C) and radioactive (^{14}C) carbon isotopes, Wang et al. (Wang, Lee, et al., 2016) meta-analysed biochar decomposition in soil and estimated its MRT. They found that biochar has a small labile C-fraction of 3%, which degrades within the first year, and a large recalcitrant C pools of 97% with an

MRT of 556 years. The large recalcitrant fraction can contribute directly to long-term C sequestration in soil.

Besides the direct C-sink effect of soil applied biochar which is considered as one of the six main negative emission technologies (Fuss et al., 2018; Schmidt, Anca-Couce, et al., 2019; Smith et al., 2019), the application of biochar may affect the dynamic of native SOC. At the beginning of biochar research, scientists were concerned that the use of biochar might cause positive priming (i.e. accelerated mineralization) of the non-pyrogenic SOC. Negative priming, however, means that decomposition is slowed down, and losses of newly incorporated (root) carbon are reduced (i.e. SOM build-up) (Kuzyakov et al., 2000). The fear of positive priming was fuelled by an early study where charcoal was added to the organic litter layer in a boreal coniferous forest. Over 10 years, accelerated decomposition of (acidic) organic matter was observed in the presence of charcoal (Wardle et al., 2008). However, the results of this particular setup in a boreal ecosystem could not be confirmed for other locations and setups by later studies. It is possible that biochar's adsorption of nitrification-inhibiting phenolic compounds from the needle litter increased N mineralization (DeLuca et al., 2006), thus enhancing decomposition of the needle raw humus material.

Numerous researchers investigated the topic of priming with incubation studies of mineral soils (arable, grassland, and forest soils) since then, often using stable isotope tracing. A meta-analysis by (Wang, Lee, et al., 2016) using 116 observations from 21 individual studies found a slight negative priming effect of 3.8% in short-term studies (<5 months) without plants and explained it by a shift in substrate utilization by the microbial biomass. Agronomically, this effect can be considered positive, as it testifies to the fact that microbial activity and thus nutrient recycling in the soil are stimulated by biochar addition. The number of long-term studies was, however, too low to draw robust conclusions on long-term biochar induced SOC priming.

More recently, Ding et al. (2018) evaluated 27 incubation studies without plants and showed that biochar properties (33.7%) had a greater effect on the increase of SOC (negative priming) than variation in soil properties. The authors further showed that it was mainly the duration of the incubation (i.e. the time since the biochar was applied to soil) that determined the outcome. On average, in all evaluated studies (without plants, i.e. fresh C input), native soil carbon was positively primed over the first 200 days. From then until the 770th day, SOC increased sharply compared with the controls (negative priming), after which the increase slowed down until the SOC remained relatively stable after almost 3 years. Overall, the biochar application led to a 40% higher SOC content compared with the control after 3 years. However, experiments without plants which deliver a continuous C-input to the soil are of limited value for extrapolating to field set-ups.

Liu et al. (2016) reported a 52% increase in SOC in a meta-analysis that included 148 direct comparisons. More recently, Bai et al. (2019) meta-analysed data comparing different climate-smart agricultural practices (conservation-tillage, cover-crops and biochar) and found that biochar represented the most effective approach for increasing SOC content (39% increase in SOC including biochar-C) compared with other strategies (<10%).

In a field study by Weng et al. (2017) in subtropical grassland in Australia, it was shown that about 25% more young, root-borne carbon remained in the soil in the 10th year after biochar application compared with the control soil without biochar. The study was not included in the meta-analysis discussed above because it included plant-C inputs. In a large-scale field trial in the Midwestern US, Blanco-Canqui et al. (2020) supplied 9.3 t ha^{-1} biochar to corn under no-till management, switchgrass and prairie grasses with the three different cropping systems being cultivated without intensive tillage. After 6 years, the soils' SOC content had increased on average by 7 t ha^{-1} carbon (in addition to the carbon introduced with the biochar) compared with 2 t ha^{-1} in the control treatments. The carbon introduced into the soil by the biochar was, thus, more than doubled by the increase in SOC after 6 years (Blanco-Canqui et al., 2020). Apart from the significant SOC increase, the authors did not detect positive agronomic effects on yield, or plant health. Both Weng's et al. (2017) and Blanco-Canqui's et al. (2020) results indicate that biochar in the field can substantially increase non-pyrogenic SOC. The overall outcome of biochar addition to vegetated ecosystems cannot be quantified by meta-studies yet, because studies that differentiate all three fluxes are challenging, they demand the use of stable isotope techniques, and are, thus, still scarce (Weng et al., 2017; Whitman & Lehmann, 2015).

3.7 | Plant-available phosphorus and mineral nitrogen species

Phosphorus (P) is a macronutrient for plants that must be added to the soil as phosphate fertilizer in intensively managed agricultural systems. However, only a portion of the fertilized phosphate is available to plants and relevant amounts of phosphate are washed out primarily through surface runoff and subsequently pollute surface waters. Besides, mineral P is a finite resource, so increasing the P fertilizer use efficiency would both minimize environmental impacts and reduce pressure on limited P resources.

Gao et al. (2019) conducted a meta-analysis of 124 studies to determine whether the application of biochar increased the plant availability of phosphate. Overall, biochar applications without blended fertilizer increased the available P in topsoil by 45% and P in microbial biomass by 48%. These results are statistically significant for those soils where plant uptake of phosphate is impaired due to iron or aluminium toxicity (Dai et al., 2017) and where P is, therefore, a limiting factor of plant growth. Hence, biochar might be a tool for reducing fertilizer application rates and environmental costs, even in soils with regular P supply.

Another study from the same year (Glaser & Lehr, 2019) only included 25 studies and 108 pairwise comparisons, because they focused on experiments without additional P fertilization. They identified in some cases much higher P uptake by plants after biochar amendment compared with the non-amended control (450% on average). However, the study did not distinguish whether plants took up soil-, fertilizer- or biochar-borne phosphorus. Because biochars from nutrient-rich biomasses such as animal manure or sewage sludge are considered P fertilizers (Wang et al., 2012) and because such biochars were used in some of the included studies, it is possible that the high average increases were due to the fertilizer effect rather than an indirect effect of soil P-reserve mobilization. Remarkably, the most increased P uptake was found in acidic soils.

In the meta-analysis by Gao et al. (2019) a 12% reduction in topsoil nitrate and an 11% reduction in ammonium content were found. This might be related to the observation that soil-applied biochar can reversibly capture significant amounts of nitrate and to a lesser extent ammonium within its pore structure, which is not entirely detected with conventional soil extraction methods (i.e. shaking for 1 h with 0.01 M CaCl, 2 M KCl, or comparable approaches). Longer and repeated extraction times are necessary to mobilize the N captured in biochar particles (Hagemann, Kammann, et al., 2017; Haider et al., 2016, 2020; Kammann et al., ,2015). Under constant plant-growth promoting moisture conditions, plants were able to retrieve the nitrate captured in biochar particles (Haider et al., 2020; Kammann et al., 2015) which could not be detected by the analytical methods used in the studies analysed by Gao et al. (2019). The same problem of inappropriate N_{min}-analysis for biochar amended soils encumbers the interpretation of data from an earlier meta-analysis (Nguyen et al., 2017) who found a similar 10–11% N_{min}-reduction in the topsoil. However, when pure biochar without nutrient enhancement is applied in large quantities to the soil, an initial reduction in plant available N due to adsorption from the soil can be expected. The N is not lost though but captured and can be released over more extended plant growth periods (Hagemann, Kammann, et al., 2017).

3.8 | Biochar in composting

Co-composting was one of the first methods to achieve agronomically measurable and economically beneficial results of biochar application in temperate climate (Kammann et al., 2016; Steiner et al., 2010). Still today, many biochar-based products on the European market are produced by co-composting biochar (EBC, internal certification data). Numerous studies published between 2015 and 2020 demonstrated positive effects of biochar on the composting process, compost properties and plant growth enhancing qualities once applied to soil (Godlewska et al., 2017; Hagemann, Joseph, et al., 2017; Hagemann, Kammann, et al., 2017; Kammann et al., 2015; Prost et al., 2012; Sanchez-Monedero et al., 2018).

In a first meta-study on the effect of biochar-compost as a soil amendment that, however, included only 14 publications, Wang et al. (2019) found that compost with co-composted biochar increased average crop yield significantly by 40% compared with the control compost without biochar. The highest yield increases occurred in soils with pH values between 4 and 5. However, it should be noted that, besides the low number of studies, the methods and conditions of composting varied widely among the studies compared. The decisive factor is not the addition of biochar but remains the composting technique itself (Kammann et al., 2016).

A meta-analysis published in 2020 found that composting releases on average one-third of the nitrogen present in biomass in gaseous forms, with an average of 1.2% of nitrogen emitted as N_2O (Zhao et al., 2020). The addition of biochar to composting could reduce nitrogen losses by 30.2% (38 pairwise comparisons). These results are supported by the finding that physical additives like biochar and zeolite were more effective at reducing the total GHG emissions (67.2%) during composting of solid wastes compared with chemical additives because of the greater mitigation of N_2O emissions (Cao et al., 2019). Hence, biochar could be an effective compost additive for reducing GHG emissions and improving the environmental performance of composting.

The state of knowledge regarding the use and mechanisms of biochar in composting was comprehensively reported in the review articles by Godlewska et al. (2017), Kammann et al. (2016), and Sanchez-Monedero et al. (2018) but, nevertheless, the N-retaining effects during composting and the agronomic effects of aerobic biochar-composts should receive further research attention. The two meta-analyses found on the topic (Cao et al., 2019 and

Zhao et al., 2020) were not selected among the 26 meta-analyses because of the limited number of original studies included (less than 100 pairwise comparisons).

3.9 | Uptake of heavy metals from contaminated soils

Based on 1813 data sets from 97 scientific publications, Peng et al. (2018) showed that biochar application to soils polluted with toxic elements (TE) led to a reduction of their uptake and incorporation into the biomass and/or the edible parts of the plants grown in them. Biochar particularly reduced the uptake of chromium (Cr, by 64%), lead (Pb, by 49%), and cadmium (Cd, by 32%). Plant uptake of copper (Cu), zinc (Zn), nickel (Ni) and manganese (Mn) were also reduced, but not always significantly so (or significantly only with certain types of biochar). No reduction was observed for arsenic (As) when untreated biochar was tested. However, special pyrolytic surface treatments, for example, with $Mg(OH)_2$ can turn biochar into a highly effective sorbent for As, which is already used in drinking water purification (Alkurdi et al., 2019; Dieguez-Alonso et al., 2018; Rajapaksha et al., 2016; Vithanage et al., 2017). Remarkably, the TE reduction effects of non-woody biochars obtained from pyrolysis of, for example, straw, husks, manure, or even sewage sludge were often more pronounced than those of woody biochars. Another meta-analysis, resuming data from 74 publications confirmed significant Cd, Pb Cu and Zn plant-uptake reduction of 38 and 39, 25 and 17% respectively (Chen et al., 2018). Generally, the higher the biochar pH, the greater was the decrease in plant heavy metal uptake.

There is a broad consensus that biochars can minimize TE contamination of soils (Hilber et al., 2017; Kloss et al., 2014; Peng et al., 2018; Tang et al., 2013) so that crop or at least biomass production becomes possible again on polluted sites where TE contamination impairs plant growth and crop quality. On slightly polluted sites, the heavy metal content of crops can be reduced below the applicable product thresholds. A prominent example here is cocoa cultivation where high geogenic background concentration of Cd may cause Cd-contents of cocoa products above new EU thresholds. Root zone applied biochar can significantly reduce cocoa beans' cadmium content (Ramtahal et al., 2019).

3.10 | Change of methane fluxes between soil and atmosphere

In the last 4 years, three major meta-analyses have been published about biochars' effect on methane fluxes between agricultural soils and the atmosphere. While Cong et al. (2018) found no significant effects of biochar, Jeffery et al. (2016) and Ji et al. (2018) showed average reduction of methane emissions from flooded soils, though mostly for pot and not for field trials.

Two basic microbial processes control soil-borne CH_4 emissions: (a) methane production by methanogenic archaea under strictly anoxic conditions (e.g. in waterlogged soils or at greater soil depth or in anoxic microsites) and (b) methane oxidation (consumption of methane) by methanotrophic bacteria, which require O_2, or by nitrite-dependent anaerobic oxidation of methane known as n-damo (Ettwig et al., 2008). For example, in a rice field, methanotrophic bacteria settle in the rhizosphere where rice roots release O_2, which leads to the oxidation of CH_4 produced by methanogenic archaea below and around the roots. The net flux between soil and atmosphere is then determined by the balance of the two processes because most CH_4 leaves rice paddy ecosystems through the aerenchyma of rice plants and less by ebullition and diffusion.

The comprehensive analysis by Jeffery et al. (2016) included 42 studies with 193 data sets on agricultural soils covered with plants and not all of them rice paddies. Here, a significant reduction of methane emissions was found, especially on sites with predominant CH_4 production, such as rice fields, while there were no apparent effects in ecosystems with dominant methane oxidation and thus already very low to zero emissions or rather net CH_4 uptake.

Ji et al. (2018) stated in a meta-analysis including 222 paired measurements from 61 publications: 'that the role of biochar in soil CH_4 mitigation potential might have been exaggerated'. The authors found, averaged across all studies, a significantly decreased of CH_4 release rates by 12% for paddy soils. However, these experimental data was mainly gained in pot trials. Field trials, on the contrary, did not deliver significant results. Moreover, the co-application of N-fertilizer weakened the measured CH_4-reduction. To investigate the underlying mechanisms and improve prediction of biochar effects on soil-related CH_4-emissions, Cong et al. (2018) did not state overall average effects but argued that the interaction of the following three soil factors: water saturation, soil texture and SOC content explain best the soil CH_4 flux responses reported for biochar additions.

Due to the high variability and insufficient systematics of the studies, it is currently only possible to speculate on the reasons for a potential increase or decrease in soil-borne CH_4 emissions. However, it should be noted that agricultural methane emissions only reach climate-relevant levels in flooded soils such as in rice cultivation, on former peat soils with near-surface water tables or after heavy and extended rainfall events. Interestingly, in wetland restauration mesocosms, the addition of biochar greatly decreased cumulative CH_4 emissions by up to 92%; the effect was most pronounced in waterlogged or field-capacity mesocosms that had received additions of compost as a source of labile C for CH_4 formation via archaeal methanogenesis (Rubin et al., 2020). It is evident that the mechanisms of reduced or increased CH_4 fluxes tied to biochar properties, soil moisture conditions and the soil microbiome deserves further research.

Co-feeding biochar to ruminants had in some experiments the effect of reduced enteric methane emissions (Leng et al., 2013). This effect could not yet be confirmed by most published studies (Schmidt et al., 2019). It was further suggested that the application of biochar in animal bedding and as an additive for liquid manure storage could reduce manure-related methane emissions (Kammann et al., 2017). However, reliable experimental data are still missing, mainly due to the complexity of methane measurements in animal housing and large manure lagoons with sufficient replicates. No meta-analysis on biochar uses in animal farming was published yet.

3.11 | Reduction of N_2O and effects on NH_3 emissions and nitrate leaching

The reduction of soil nitrous oxide emissions through biochar amendment is one of the best-documented effects of its use. The first meta-analysis on this topic was already conducted in 2014 (Cayuela et al., 2014). It showed a mean reduction of N_2O emissions when using biochar of 49% across all studies, although they were mostly laboratory-based studies with high biochar application rates.

In a meta-analysis including only results from field studies Verhoeven et al. (2017) found an average decrease in N_2O emissions of 12.4%. However, considering the high diversity of biochars used as well as cropping systems and pedo-climatic conditions, the number of direct comparisons included was relatively low (122). The authors highlighted the importance of data collection at field scale, specifically the necessity of long-term studies across varied cropping systems, and the assessment of yield-scaled N_2O emissions.

A more recent meta-analysis, which evaluated 88 studies, showed a reduction in cumulative N_2O emissions (435 paired records) of 38% across all studies (field and greenhouse; fertilized and unfertilized) and 46% when only experiments with mineral fertilization were considered (Borchard et al., 2019). Application rates below 10 t ha^{-1} had lower effects. The largest reductions were achieved using biochars with a production temperature of 600–700°C and using woody feedstock for biochar production. Based on these three meta-analyses, a clear consensus can be stated: Biochar soil application reduces agricultural N_2O emissions. Further research on the permanence of N_2O emission reduction is still needed because the vast majority of (field) studies primarily measured emission reduction in the first year after application. However, Hagemann, Joseph, et al. (2017) could show that biochar reduced N_2O emissions from a field fertilized with mineral N by 63% in the third year after application.

Cumulative nitrate leaching (120 paired records) was significantly reduced by 26% to 32% by biochar in studies with an observation period of at least 30 days. Longer study duration was associated with more significant nitrate leaching reductions (Borchard et al., 2019). This result is consistent with the lower extraction of mineral N found using traditional methods as reported in section 3.7. and the discovery of reversible uptake of nitrate in biochar particles after aging in soil or compost, which results in the formation of an organic coating that enables biochar to more effectively retain anions (Hagemann, Joseph, et al., 2017; Hagemann, Kammann, et al., 2017; Haider et al., 2016; Joseph et al., 2017; Kammann et al., 2015). Also, low-molecular-weight organic acids in aqueous solution (Achor et al. 2020) and the general presence of acidity, respective a lowered pH in solution (Fidel et al., 2018), have been shown to increase the ability of biochars to immobilize nitrate. In the above-mentioned wetland restauration study of Rubin et al. (2020), where up to 10% biochar addition decreased nitrate leaching up to 92%, the soil had a low pH of 4.6. Hence, organic coating and organic acid adsorption may be part of the overall mechanisms underlying the meta-study result of Borchard et al. (2019) on nitrate leaching in the presence of biochar.

In a meta-analysis of 41 studies and 144 pairwise comparisons, summarizing the effect of biochar on gaseous ammonia losses from agricultural field, no significant effect was observed. A high variation of results, with increases or decreases in NH_3-emissions, was found depending on soil and type of biochar used (Sha et al., 2019). For example, the application of alkaline biochar to highly acidic soils increased ammonia volatilization and emissions. In contrast, when the biochar was applied together with mineral or organic fertilizer (<200 kg N ha^{-1}), or when the biochar was acidified, both resulted in significantly reduced ammonia emissions. Looking at ammonia, relevant emissions occur during storage and application of (liquid) manure. However, only few studies are available, also due to complexity of gas sampling in animal housing and during application of liquid manure. Additionally, effects of biochar will strongly depend on the method and timing of biochar use (feed vs. bedding vs. manure) which impact further the comparability of studies.

So far, however, there are no studies that investigated N_2O, NH_3 emissions or nitrate leaching from biochar-based fertilization with root-zone application, where fertilizer is exposed to an environment with locally very high biochar concentrations although the overall biochar application rate may be as low as 1 t ha^{-1}.

4 | CONCLUSIONS AND FUTURE CONSIDERATIONS

In 26 meta-analyses published since 2016, encompassing more than 1500 scientific publications, the application of biochar delivered mean positive effects for all investigated parameters regarding performance and environmental impact of land cultivation. No negative agronomic or environmental effects were consistently demonstrated for any of the parameters evaluated. Even if there is a certain tendency in scientific publication practice to publish rather significant and positive results (publication bias), the number of studies and the selection criteria used here nevertheless stands for a robust data basis.

These considerable improvements in such a broad spectrum of agronomic parameters (Figure 2) do not mean that all major questions regarding the use of biochar have already been answered nor that it should automatically be considered an economically viable practice. The question of economic viability arises particularly in Central-Northern Europe, northern North America and other regions with annual mean temperatures below 10°C, where systematic yield increases by biochar application could not be achieved yet.

However, since around 2015, new agronomic methods of biochar application have been gaining attention. Today, biochar is more often used in combination with fertilizers and biochar-based fertilizers that are applied, for example, in the root zone, at significantly lower application rates of 0.5 – 2 t (DM) per hectare which may be repeated annually (Blackwell et al., 2010; Cornelissen et al., 2013; Joseph et al., 2013; Liang et al., 2021; Schmidt et al., 2017a,2017b; Ye et al., 2020). The biomass necessary for producing these lower biochar amounts may be either obtained from the agricultural land directly (e.g. crop residue plus agroforestry, hedgerow pruning of landscape biodiversity or of wind-protection elements) or could be purchased, as these lower doses of biochar may be financially more affordable. However, scientific literature on these new methods is still rare and only a few of the reviewed meta-studies used data from those recent experiments. However, the investigation of effects of the application of larger amounts of biochar are meaningful for (a) the identification of possible negative effects (b) achievable biochar effects which can be further optimized with tailored biochars for specific soils and applications, with a spectrum of organic, mineral, and biological enhancements, and with advanced application strategies such as micronized biochar with drip irrigation and (c) evaluating biochar as a soil carbon sequestration and hence CDR measure.

Although scientific studies are primarily concerned with investigating underlying mechanisms and meta-analyses summarize overall effects, industrial research and development aim to achieve optimized products with the highest possible efficiencies. If special biochar products are developed for specific applications based on the scientific results from the meta-analyses, higher increases in yield, root growth, SOC, nutrient efficiency and GHG emission reductions than those reported here might be possible.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Achor, S., Aravis, C., Heaney, N., Odion, E., & Lin, C. (2020). Response of organic acid-mobilized heavy metals in soils to biochar application. *Geoderma*, *378*, 114628. https://doi.org/10.1016/J.GEODERMA.2020.114628

Alkurdi, S. S. A., Herath, I., Bundschuh, J., Al-Juboori, R. A., Vithanage, M., & Mohan, D. (2019). Biochar versus bone char for a sustainable inorganic arsenic mitigation in water: What needs to be done in future research? *Environment International*, *127*, 52–69. https://doi.org/10.1016/J.ENVINT.2019.03.012

Allen, R. L. (1846). *A brief compend of American agriculture*. Saxton & Miles.

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P., Tao, B., Hui, D., Yang, J., & Matocha, C. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Global Change Biology*, *25*(8), 2591–2606. https://doi.org/10.1111/gcb.14658

Barber, S. T., Yin, J., Draper, K., & Trabold, T. A. (2018). Closing nutrient cycles with biochar- from filtration to fertilizer. *Journal of Cleaner Production*, *197*, 1597–1606. https://doi.org/10.1016/J.JCLEPRO.2018.06.136

Barghi, M. H. (2018). Use of capillary action to control soil moisture [doctoral thesis at University of Birmingham]. https://etheses.bham.ac.uk//id/eprint/9055/1/Heidar_Barghi2019PhD.pdf.

Bartoli, M., Giorcelli, M., Jagdale, P., Rovere, M., & Tagliaferro, A. (2020). A review of non-soil biochar applications. *Materials (Basel, Switzerland)*, *13*(2), https://doi.org/10.3390/ma13020261

Bezerra, J., Turnhout, E., Vasquez, I. M., Rittl, T. F., Arts, B., & Kuyper, T. W. (2019). The promises of the Amazonian soil: Shifts in discourses of Terra Preta and biochar. *Journal of Environmental Policy & Planning*, *21*(5), 623–635. https://doi.org/10.1080/1523908X.2016.1269644

Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy*, *5*(2), 202–214. https://doi.org/10.1111/gcbb.12037

Blackwell, P., Krull, E., Butler, G., Herbert, A., & Solaiman, Z. (2010). Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: An agronomic and economic perspective. *Soil Research*, *48*(7), 531–545. https://doi.org/10.1071/SR10014

Blanco-Canqui, H., Laird, D. A., Heaton, E. A., Rathke, S., & Acharya, B. S. (2020). Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. *GCB Bioenergy*, *12*(4), 240–251. https://doi.org/10.1111/gcbb.12665

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364. https://doi.org/10.1016/J.SCITOTENV.2018.10.060

Bruun, E. W., Petersen, C. T., Hansen, E., Holm, J. K., & Hauggaard-Nielsen, H. (2014). Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. *Soil Use and Management*, *30*(1), 109–118. https://doi.org/10.1111/sum.12102

Cao, Y., Wang, X., Bai, Z., Chadwick, D., Misselbrook, T., G. Sommer, S., Qin, W., & Ma, L. (2019). Mitigation of ammonia, nitrous oxide and methane emissions during solid waste composting with different additives: A meta-analysis. *Journal of Cleaner Production*, *235*, 626–635. https://doi.org/10.1016/J.JCLEPRO.2019.06.288

Cardinael, R., Chevallier, T., Cambou, A., Béral, C., Barthès, B. G., Dupraz, C., Durand, C., Kouakoua, E., & Chenu, C. (2017). Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. *Agriculture, Ecosystems & Environment*, *236*, 243–255. https://doi.org/10.1016/J.AGEE.2016.12.011

Cato, M. P. (1935). *On agriculture*. Harvard University Press.

Cayuela, M. L., van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., & Sánchez-Monedero, M. A. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, *191*, 5–16. https://doi.org/10.1016/J.AGEE.2013.10.009

Chen, D., Liu, X., Bian, R., Cheng, K., Zhang, X., Zheng, J., Joseph, S., Crowley, D., Pan, G., & Li, L. (2018). Effects of biochar on availability and plant uptake of heavy metals - A meta-analysis. *Journal of Environmental Management*, *222*, 76–85. https://doi.org/10.1016/j.jenvman.2018.05.004

Chew, J., Zhu, L., Nielsen, S., Graber, E., Mitchell, D. R. G., Horvat, J., Mohammed, M., Liu, M., van Zwieten, L., Donne, S., Munroe, P., Taherymoosavi, S., Pace, B., Rawal, A., Hook, J., Marjo, C., Thomas, D. S., Pan, G., Li, L., Fan, X. (2020). Biochar-based fertilizer: Supercharging root membrane potential and biomass yield of rice. *Science of the Total Environment*, *713*, 136431. https://doi.org/10.1016/j.scitotenv.2019.136431

Cong, W., Meng, J., & Ying, S. C. (2018). Impact of soil properties on the soil methane flux response to biochar addition: A meta-analysis. *Environmental Science. Processes & Impacts*, *20*(9), 1202–1209. https://doi.org/10.1039/c8em00278a

Conte, P., & Schmidt, H.-P. (2017). Soil-water interactions unveiled by fast field cycling NMR relaxometry. *eMagRes*, *6*(4), 1–12. https://doi.org/10.1002/9780470034590.emrstm1535

Coppola, A. I., Wiedemeier, D. B., Galy, V., Haghipour, N., Hanke, U. M., Nascimento, G. S., Usman, M., Blattmann, T. M., Reisser, M., Freymond, C. V., Zhao, M., Voss, B., Wacker, L., Schefuß, E., Peucker-Ehrenbrink, B., Abiven, S., Schmidt, M. W. I., & Eglinton, T. I. (2018). Global-scale evidence for the refractory nature of riverine black carbon. *Nature Geoscience*, *11*(8), 584–588. https://doi.org/10.1038/s41561-018-0159-8

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G., Rutherford, D., Sparrevik, M., Hale, S., Obia, A., & Mulder, J. (2013). Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. *Agronomy*, *3*(2), 256–274. https://doi.org/10.3390/agronomy3020256

Dai, Y., Zheng, H., Jiang, Z., & Xing, B. (2020). Combined effects of biochar properties and soil conditions on plant growth: A meta-analysis. *Science of the Total Environment*, *713*, 136635. https://doi.org/10.1016/J.SCITOTENV.2020.136635

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P. C., & Xu, J. (2017). Potential role of biochars in decreasing soil acidification - A critical review. *Science of the Total Environment*, *581–582*, 601–611. https://doi.org/10.1016/j.scitotenv.2016.12.169

DeLuca, T. H., MacKenzie, M. D., Gundale, M. J., & Holben, W. E. (2006). Wildfire-produced charcoal directly influences nitrogen C-cycling in ponderosa pine forests. *Soil Science Society of America Journal*, *70*(2), 448–453. https://doi.org/10.2136/sssaj2005.0096

Dieguez-Alonso, A., Anca-Couce, A., Frišták, V., Moreno-Jiménez, E., Bacher, M., Bucheli, T., Cimò, G., Conte, P., Hagemann, N., Haller, A., Hilber, I., Husson, O., Kammann, C. I., Kienzl, N., Leifeld, J., Rosenau, T., Soja, G., & Schmidt, H.-P. (2018). Designing biochar properties through the blending of biomass feedstock with metals: Impact on oxyanions adsorption behavior. *Chemosphere*, *214*, 743–753. https://doi.org/10.1016/J.CHEMOSPHERE.2018.09.091

Dietrich, C. C., Rahaman, M. A., Robles-Aguilar, A. A., Latif, S., Intani, K., Müller, J., & Jablonowski, N. D. (2020). Nutrient loaded biochar doubled biomass production in juvenile maize plants (Zea mays L.). *Agronomy*, *10*(4), 1–12. https://doi.org/10.3390/agronomy10040567

Ding, F., Van Zwieten, L., Zhang, W., Weng, Z., Shi, S., Wang, J., & Meng, J. (2018). A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. *Journal of Soils and Sediments*, *18*(4), 1507–1517. https://doi.org/10.1007/s11368-017-1899-6

Downie, A. E., Van Zwieten, L., Smernik, R. J., Morris, S., & Munroe, P. R. (2011). Terra Preta Australis: Reassessing the carbon storage capacity of temperate soils. *Agriculture, Ecosystems & Environment*, *140*(1–2), 137–147. https://doi.org/10.1016/J.AGEE.2010.11.020

EBC. (2020). Certification of the Carbon Sink Potential of Biochar. Ithaka Institute, Arbaz, Switzerland. http://european-biochar.org/en/c-sink. Version 2.1E of 1st February 2021.

Edeh, I. G., Mašek, O., & Buss, W. (2020). A meta-analysis on biochar's effects on soil water properties – New insights and future research challenges. *Science of the Total Environment*, *714*, 136857. https://doi.org/10.1016/j.scitotenv.2020.136857

Edenborn, S. L., Johnson, L. M. K., Edenborn, H. M., Albarran-Jack, M. R., & Demetrion, L. D. (2018). Amendment of a hardwood biochar with compost tea: effects on plant growth, insect damage and the functional diversity of soil microbial communities. *Biological Agriculture & Horticulture*, *34*(2), 88–106. https://doi.org/10.1080/01448765.2017.1388847

Embren, B. (2016). Planting urban trees with biochar. *The Biochar Journal*, www.biochar-journal.org/en/ct/77.

Ettwig, K. F., Shima, S., van de Pas-Schoonen, K. T., Kahnt, J., Medema, M. H., op den Camp, H. J. M., Jetten, M. S. M., & Strous, M. (2008). Denitrifying bacteria anaerobically oxidize methane in the absence of *Archaea*. *Environmental Microbiology*, *10*(11), 3164–3173. https://doi.org/10.1111/j.1462-2920.2008.01724.x

Farrar, M. B., Wallace, H. M., Xu, C. Y., Nguyen, T. T. N., Tavakkoli, E., Joseph, S., & Bai, S. H. (2019). Short-term effects of organo-mineral enriched biochar fertiliser on ginger yield and nutrient cycling. *Journal of Soils and Sediments*, *19*(2), 668–682. https://doi.org/10.1007/s11368-018-2061-9

Fidel, R. B., Laird, D. A., & Spokas, K. A. (2018). Sorption of ammonium and nitrate to biochars is electrostatic and pH-dependent. *Scientific Reports*, *8*(1), 17627. https://doi.org/10.1038/s41598-018-35534-w

Frausin, V., Fraser, J. A., Narmah, W., Lahai, M. K., Winnebah, T. R. A., Fairhead, J., & Leach, M. (2014). "God made the soil, but we made it fertile": Gender, knowledge, and practice in the formation and use of african dark earths in Liberia and Sierra Leone. *Human Ecology*, *42*(5), 695–710. https://doi.org/10.1007/s10745-014-9686-0

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Gao, S., DeLuca, T. H., & Cleveland, C. C. (2019). Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of the Total Environment*, *654*, 463–472. https://doi.org/10.1016/J.SCITOTENV.2018.11.124

Gao, Y., Shao, G., Lu, J., Zhang, K., Wu, S., & Wang, Z. (2020). Effects of biochar application on crop water use efficiency depend on experimental conditions: A meta-analysis. *Field Crops Research*, *249*, 107763. https://doi.org/10.1016/J.FCR.2020.107763

Glaser, B. (2007). Prehistorically modified soils of central Amazonia: A model for sustainable agriculture in the twenty-first century. *Philosophical Transactions of the Royal Society B-Biological Sciences*, *362*(1478), 187–196. https://doi.org/10.1098/Rstb.2006.1978

Glaser, B., & Birk, J. (2012). State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica Et Cosmochimica Acta*, *82*, 39–51. https://doi.org/10.1016/j.gca.2010.11.029

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The "Terra Preta" phenomenon: A model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*(1), 37–41. https://doi.org/10.1007/s001140000193

Glaser, B., & Lehr, V.-I. (2019). Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. *Scientific Reports*, *9*(1), 9338. https://doi.org/10.1038/s41598-019-45693-z

Glaser, B., Wiedner, K., Seelig, S., Schmidt, H.-P., & Gerber, H. (2014). Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. *Agronomy for Sustainable Development*, *35*(2), 667–678. https://doi.org/10.1007/s13593-014-0251-4

Godlewska, P., Schmidt, H. P., Ok, Y. S., & Oleszczuk, P. (2017). Biochar for composting improvement and contaminants reduction. A review. *Bioresource Technology*, *246*, 193–202. https://doi.org/10.1016/j.biortech.2017.07.095

Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. *Nature*, *555*(7695), 175–182. https://doi.org/10.1038/nature25753

Hagemann, N., Joseph, S., Schmidt, H., Kammann, C. I., Harter, J., Borch, T., Young, R. B., Varga, K., Taherymoosavi, S., Elliott, K. W., Albu, M., Mayrhofer, C., Obst, M., Conte, P., Dieguez-, A., Orsetti, S., Subdiaga, E., Behrens, S., Kappler, A., … Sciences, C. (2017). Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. *Nature Communications*, *8*(1), 1089–1101. https://doi.org/10.1038/s41467-017-01123-0

Hagemann, N., Kammann, C. I., Schmidt, H.-P., Kappler, A., & Behrens, S. (2017). Nitrate capture and slow release in biochar amended compost and soil. *PLoS One*, *12*(2), e0171214. https://doi.org/10.1371/journal.pone.0171214

Hagemann, N., Spokas, K., Schmidt, H.-P., Kägi, R., Böhler, M. A., & Bucheli, T. D. (2018). Activated carbon, biochar and charcoal: Linkages and synergies across pyrogenic carbon's ABCs. *Water (Switzerland)*, *10*(2), 182. https://doi.org/10.3390/w10020182

Haider, G., Joseph, S., Steffens, D., Müller, C., Taherymoosavi, S., Mitchell, D., & Kammann, C. I. (2020). Mineral nitrogen captured in field-aged biochar is plant-available. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-70586-x

Haider, G., Steffens, D., Müller, C., & Kammann, C. I. (2016). Standard extraction methods may underestimate nitrate stocks captured by field-aged biochar. *Journal of Environment Quality*, *45*(4), 1196–1204. https://doi.org/10.2134/jeq2015.10.0529

Hammes, K., Torn, M. S., Lapenas, A. G., & Schmidt, M. W. I. (2008). Centennial black carbon turnover observed in a Russian steppe soil. *Biogeosciences*, *5*(5), 1339–1350. https://doi.org/10.5194/bg-5-1339-2008

He, Y., Yao, Y., Ji, Y., Deng, J., Zhou, G., Liu, R., Shao, J., Zhou, L., Li, N., Zhou, X., & Bai, S. H. (2020). Biochar amendment boosts photosynthesis and biomass in C_3 but not C_4 plants: A global synthesis. *GCB Bioenergy*, *12*(8), 605–617. https://doi.org/10.1111/gcbb.12720

Hilber, I., Bastos, A. C., Loureiro, S., Soja, G., Marz, A., Cornelissen, G., & Bucheli, T. D. (2017). The different faces of biochar: Contamination risk versus remediation tool. *Journal of Environmental Engineering and Landscape Management*, *25*(2), 86–104. https://doi.org/10.3846/16486897.2016.1254089

Hungate, B. A., van Groeningen, K.-J., Six, J., Jastrow, J. D., Luo, Y., de Graaff, M.-A., van Kessel, C., & Osenberg, C. W. (2009). Assessing the effect of elevated carbon dioxide on soil carbon: A comparison of four meta-analyses. *Global Change Biology*, *15*(8), 2020–2034. https://doi.org/10.1111/j.1365-2486.2009.01866.x

Ippolito, J. A., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizabal, T., Cayuela, M. L., Sigua, G., Novak, J., Spokas, K., & Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar*, *2*(4), 421–438. https://doi.org/10.1007/s42773-020-00067-x

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, *12*(5), 053001. https://doi.org/10.1088/1748-9326/aa67bd

Jeffery, S., Abalos, D., Spokas, K., & Verheijen, F. G. A. (2014). Biochar for Environmental Management 2 - Biochar effects on crop yield. 299–324.

Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry*, *101*, 251–258. https://doi.org/10.1016/J.SOILBIO.2016.07.021

Jeffery, S., Verheijen, F., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, *144*(1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Ji, C., Jin, Y., Li, C., Chen, J., Kong, D., Yu, K., Liu, S., & Zou, J. (2018). Variation in soil methane release or uptake responses to biochar amendment: A separate meta-analysis. *Ecosystems*, *21*(8), 1692–1705. https://doi.org/10.1007/s10021-018-0248-y

Joseph, S., Graber, E. R., Chia, C., Munroe, P., Donne, S., Thomas, T., Nielsen, S., Marjo, C., Rutlidge, H., Pan, G., Li, L., Taylor, P., Rawal, A., & Hook, J. (2013). Shifting paradigms: Development of high-efficiency biochar fertilizers based on nano-structures and soluble components. *Carbon Management*, *4*(3), 323–343. https://doi.org/10.4155/cmt.13.23

Joseph, S., Husson, O., Graber, E., van Zwieten, L., Taherymoosavi, S., Thomas, T., Nielsen, S., Ye, J., Pan, G., Chia, C., Munroe, P., Allen, J., Lin, Y., Fan, X., & Donne, S. (2015). The electrochemical properties of biochars and how they affect soil redox properties and processes. *Agronomy*, *5*(3), 322–340. https://doi.org/10.3390/agronomy5030322

Joseph, S., Kammann, C. I., Shepherd, J. G., Conte, P., Schmidt, H.-P., Hagemann, N., Rich, A. M., Marjo, C. E., Allen, J., Munroe, P., Mitchell, D. R. G., Donne, S., Spokas, K., & Graber, E. R. (2017). Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Science of the Total Environment*, *618*, 1210–1223. https://doi.org/10.1016/j.scitotenv.2017.09.200

Kammann, C. I., Glaser, B., & Schmidt, H.-P. (2016). Combining biochar and organic amendments. In S. Shackley, G. Ruysschaert, K. Zwart, & B. Glaser (Eds.), *Biochar in European soils and agriculture: Science and practice* (Earthscan, pp. 136–164). Routledge. https://doi.org/10.4324/9781315884462

Kammann, C., Ippolito, J., Hagemann, N., Borchard, M., Cayuela, J., Estavillo, T., Fuertes-Mendizabal, T., Jeffery, S., Kern, J., Novak, J., Rasse, D., Saarnio, S., Schmidt, H., Spokas, K., & Wrage-Mönnig, N. (2017). Biochar as a tool to reduce the agricultural greenhouse-gas burden - knowns, unknowns and future research needs. *Journal of Environmental Engineering and Landscape Management*, *25*(2), 114–139. https://doi.org/10.3846/16486897.2017.1319375

Kammann, C., Ratering, S., Eckhard, C., & Müller, C. (2012). Biochar and hydrochar effects on greenhouse gas (carbon dioxide, nitrous oxide, and methane) fluxes from soils. *Journal of Environment Quality*, *41*(4), 1052. https://doi.org/10.2134/jeq2011.0132

Kammann, C. I., Schmidt, H.-P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., Koyro, H.-W., Conte, P., & Stephen, J. (2015). Plant growth improvement mediated by nitrate capture in co-composted biochar. *Scientific Reports*, *5*, 11080–11092. https://doi.org/10.1038/srep11080

Kätterer, T., Bolinder, M. A., Andrén, O., Kirchmann, H., & Menichetti, L. (2011). Roots contribute more to refractory soil organic matter than above-ground crop residues, as revealed by a long-term field experiment. *Agriculture, Ecosystems and Environment*, *141*(1–2), 184–192. https://doi.org/10.1016/j.agee.2011.02.029

Kern, J., Giani, L., Teixeira, W., Lanza, G., & Glaser, B. (2019). What can we learn from ancient fertile anthropic soil (Amazonian Dark Earths, shell mounds, Plaggen soil) for soil carbon sequestration? *Catena*, *172*, 104–112. https://doi.org/10.1016/J.CATENA.2018.08.008

Kloss, S., Zehetner, F., Buecker, J., Oburger, E., Wenzel, W. W., Enders, A., Lehmann, J., & Soja, G. (2014). Trace element biogeochemistry in the soil-water-plant system of a temperate agricultural soil amended with different biochars. *Environmental Science and Pollution Research*, *22*, 4513–4526. https://doi.org/10.1007/s11356-014-3685-y

Koricheva, J., & Gurevitch, J. (2014). Uses and misuses of meta-analysis in plant ecology. *Journal of Ecology*, *102*(4), 828–844. https://doi.org/10.1111/1365-2745.12224

Kuzyakov, Y., Friedel, J., & Stahr, K. (2000). Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry*, *32*(11–12), 1485–1498. https://doi.org/10.1016/S0038-0717(00)00084-5

Laird, D. A. (2008). The Charcoal Vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, *100*(1), 178. https://doi.org/10.2134/agronj2007.0161

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B. P., Sohi, S. P., & Zimmerman, A. R. (2015). Persistence of biochar in soil. In J. Lehmann, & S. D. Joseph (Eds.), *Biochar for environmental management* (2nd ed., pp. 235–299). Routledge.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – A review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 395–419. https://doi.org/10.1007/s11027-005-9006-5

Lehmann, J., Hansel, C. M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J. P., Torn, M. S., Wieder, W. R., & Kögel-Knabner, I. (2020). Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience*, *13*(8), 529–534. https://doi.org/10.1038/s41561-020-0612-3

Lehmann, J., & Joseph, S. (2009). *Biochar for environmental management: Science and technology*. Earthscan.

Leifeld, J., Alewell, C., Bader, C., Krüger, J. P., Mueller, C. W., Sommer, M., Steffens, M., & Szidat, S. (2018). Pyrogenic carbon contributes substantially to carbon storage in intact and degraded northern peatlands. *Land Degradation & Development*, *29*(7), 2082–2091. https://doi.org/10.1002/ldr.2812

Leng, R. A., Preston, T. R., & Inthapanya, S. (2013). Biochar reduces enteric methane and improves growth and feed conversion in local " Yellow " cattle fed cassava root chips and fresh cassava foliage. *LRR*, *24*(11), 2–7. http://www.lrrd.org/lrrd24/6/sang24103.htm.

Li, X., Wang, T., Chang, S. X., Jiang, X., & Song, Y. (2020). Biochar increases soil microbial biomass but has variable effects on microbial diversity: A meta-analysis. *Science of the Total Environment*, *749*, 141593. https://doi.org/10.1016/J.SCITOTENV.2020.141593

Liang, J.-F., Li, Q.-W., Gao, J.-Q., Feng, J.-G., Zhang, X.-Y., Wu, Y.-Q., & Yu, F.-H. (2021). Biochar rhizosphere addition promoted Phragmites australis growth and changed soil properties in the Yellow River Delta. *Science of the Total Environment*, *761*, 143291. https://doi.org/10.1016/J.SCITOTENV.2020.143291

Lin, L., & Chu, H. (2018). Quantifying publication bias in meta-analysis. *Biometrics*, *74*(3), 785–794. https://doi.org/10.1111/biom.12817

Liu, Q., Liu, B., Zhang, Y., Hu, T., Lin, Z., Liu, G., Wang, X., Ma, J., Wang, H., Jin, H., Ambus, P., Amonette, J. E., & Xie, Z. (2019). Biochar application as a tool to decrease soil nitrogen losses (NH_3 volatilization, N_2O emissions, and N leaching) from croplands: Options and mitigation strength in a global perspective. *Global Change Biology*, *25*(6), 2077–2093. https://doi.org/10.1111/gcb.14613

Liu, Q., Zhang, Y., Liu, B., Amonette, J. E., Lin, Z., Liu, G., Ambus, P., & Xie, Z. (2018). How does biochar influence soil N cycle? A meta-analysis. *Plant and Soil*, *426*(1–2), 211–225. https://doi.org/10.1007/s11104-018-3619-4

Liu, Z., Dugan, B., Masiello, C. A., Barnes, R. T., Gallagher, M. E., & Gonnermann, H. (2016). Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar-sand mixtures. *Journal of Hydrology*, *533*, 461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007

Makoto, K., Tamai, Y., Kim, Y. S., & Koike, T. (2010). Buried charcoal layer and ectomycorrhizae cooperatively promote the growth of Larix gmelinii seedlings. *Plant and Soil*, *327*(1), 143–152. https://doi.org/10.1007/s11104-009-0040-z

Nguyen, T. T. N., Xu, C.-Y., Tahmasbian, I., Che, R., Xu, Z., Zhou, X., Wallace, H. M., & Bai, S. H. (2017). Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. *Geoderma*, *288*, 79–96. https://doi.org/10.1016/J.GEODERMA.2016.11.004

Ogawa, M., & Okimori, Y. (2010). Pioneering works in biochar research, Japan. *Australian Journal of Soil Research*, *48*(7), 489. https://doi.org/10.1071/SR10006

Omara, P., Aula, L., Oyebiyi, F. B., Eickho, E. M., Carpenter, J., & Raun, W. R. (2020). Biochar application in combination with inorganic nitrogen improves maize grain yield, nitrogen uptake, and use efficiency in temperate soils. *Agronomy*, *10*(9), 1241. https://doi.org/10.3390/agronomy10091241

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*, *274*, 28–34. https://doi.org/10.1016/J.GEODERMA.2016.03.029

Paneque, M., De la Rosa, J. M., Franco-Navarro, J. D., Colmenero-Flores, J. M., & Knicker, H. (2016). Effect of biochar amendment on morphology, productivity and water relations of sunflower plants under non-irrigation conditions. *Catena*, *147*, 280–287. https://doi.org/10.1016/J.CATENA.2016.07.037

Pazzagli, P. T., Weiner, J., & Liu, F. (2016). Effects of CO2 elevation and irrigation regimes on leaf gas exchange, plant water relations, and water use efficiency of two tomato cultivars. *Agricultural Water Management*, *169*, 26–33. https://doi.org/10.1016/J.AGWAT.2016.02.015

Peng, X., Deng, Y., Peng, Y., & Yue, K. (2018). Effects of biochar addition on toxic element concentrations in plants: A meta-analysis. *Science of the Total Environment*, *616–617*, 970–977. https://doi.org/10.1016/J.SCITOTENV.2017.10.222

Philibert, A., Loyce, C., & Makowski, D. (2012). Assessment of the quality of meta-analysis in agronomy. *Agriculture, Ecosystems & Environment*, *148*, 72–82. https://doi.org/10.1016/J.AGEE.2011.12.003

Pokharel, P., Ma, Z., & Chang, S. X. (2020). Biochar increases soil microbial biomass with changes in extra- and intracellular enzyme activities: A global meta-analysis. *Biochar*, *2*(1), 65–79. https://doi.org/10.1007/s42773-020-00039-1

Prost, K., Borchard, N., Siemens, J., Kautz, T., Séquaris, J., Möller, A., & Amelung, W. (2012). Biochar affected by composting with farmyard manure. *Journal of Environmental Quality*, *42*(1), 164–172. https://doi.org/10.2134/jeq2012.0064

Rajapaksha, A. U., Chen, S. S., Tsang, D. C. W., Zhang, M., Vithanage, M., Mandal, S., Gao, B., Bolan, N. S., & Sik, Y. (2016). Engineered / designer biochar for contaminant removal / immobilization from soil and water : Potential and implication of biochar modification. *Chemosphere*, *148*, 276–291. https://doi.org/10.1016/j.chemosphere.2016.01.043

Ramtahal, G., Umaharan, P., Hanuman, A., Davis, C., & Ali, L. (2019). The effectiveness of soil amendments, biochar and lime, in mitigating cadmium bioaccumulation in Theobroma cacao L. *Science of the Total Environment*, *693*, 133563. https://doi.org/10.1016/j.scitotenv.2019.07.369

Rasse, D. P., Rumpel, C., & Dignac, M. F. (2005). Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. *Plant and Soil*, *269*(1–2), 341–356. https://doi.org/10.1007/s11104-004-0907-y

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A Systematic Review and meta-analysis. *Geoderma*, *361*, 114055. https://doi.org/10.1016/J.GEODERMA.2019.114055

Reisser, M., Purves, R. S., Schmidt, M. W. I., & Abiven, S. (2016). Pyrogenic carbon in soils: A literature-based inventory and a global estimation of its content in soil organic carbon and stocks. *Frontiers in Earth Science*, *4*(August), 1–14. https://doi.org/10.3389/feart.2016.00080

Rubin, R. L., Anderson, T. R., & Ballantine, K. A. (2020). Biochar simultaneously reduces nutrient leaching and greenhouse gas emissions in restored wetland soils. *Wetlands*, *40*(6), 1981–1991. https://doi.org/10.1007/s13157-020-01380-8

Sanchez-Monedero, M. A., Cayuela, M. L., Roig, A., Jindo, K., Mondini, C., & Bolan, N. (2018). Role of biochar as an additive in organic waste composting. *Bioresource Technology*, *247*, 1155–1164. https://doi.org/10.1016/j.biortech.2017.09.193

Schmidt, H.-P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W., & Kammann, C. (2019). Pyrogenic carbon capture and storage. *GCB Bioenergy*, *11*(4), 573–591. https://doi.org/10.1111/gcbb.12553

Schmidt, H.-P., Hagemann, N., Draper, K., & Kammann, C. (2019). The use of biochar in animal feeding. *PeerJ*, *7*, e7373. https://doi.org/10.7717/peerj.7373

Schmidt, H.-P., Pandit, B. H., Cornelissen, G., & Kammann, C. I. (2017). Biochar-based fertilization with liquid nutrient enrichment: 21 field trials covering 13 crop species in Nepal. *Land Degradation and Development*, *28*(8), 2324–2342. https://doi.org/10.1002/ldr.2761

Schmidt, H. P., Pandit, B., Cornelissen, G., & Kammann, C. I. (2017). Biochar-based fertilization with liquid nutrient enrichment: 21 field trials covering 13 crop species in Nepal. *Land Degradation & Development*, *28*(8), 2324–2342. https://doi.org/10.1002/ldr.2761

Schmidt, H.-P., Pandit, B., Martinsen, V., Cornelissen, G., Conte, P., & Kammann, C. (2015). Fourfold increase in pumpkin yield in response to low-dosage root zone application of urine-enhanced biochar to a fertile tropical soil. *Agriculture*, *5*(3), 723–741. https://doi.org/10.3390/agriculture5030723

Sha, Z., Li, Q., Lv, T., Misselbrook, T., & Liu, X. (2019). Response of ammonia volatilization to biochar addition: A meta-analysis. *Science of the Total Environment*, *655*, 1387–1396. https://doi.org/10.1016/J.SCITOTENV.2018.11.316

Shi, W., Ju, Y., Bian, R., Li, L., Joseph, S., Mitchell, D. R. G., Munroe, P., Taherymoosavi, S., & Pan, G. (2020). Biochar bound urea boosts plant growth and reduces nitrogen leaching. *Science of the Total Environment*, *701*, 134424. https://doi.org/10.1016/J.SCITOTENV.2019.134424

Sigmund, G., Hüffer, T., Hofmann, T., & Kah, M. (2017). Biochar total surface area and total pore volume determined by N2 and CO2 physisorption are strongly influenced by degassing temperature. *Science of the Total Environment*, *580*, 770–775. https://doi.org/10.1016/J.SCITOTENV.2016.12.023

Smith, P., Adams, J., Beerling, D. J., Beringer, T., Calvin, K. V., Fuss, S., Griscom, B., Hagemann, N., Kammann, C., Kraxner, F., Minx, J. C., Popp, A., Renforth, P., Vicente Vicente, J. L., & Keesstra, S. (2019). Impacts of land-based greenhouse gas removal options on ecosystem services and the united nations sustainable development goals. *Annual Review of Environment and Resources*, *44*(1), annurev-environ-101718-033129. https://doi.org/10.1146/annurev-environ-101718-033129

Solomon, D., Lehmann, J., Fraser, J. A., Leach, M., Amanor, K., Frausin, V., Kristiansen, S. M., Millimouno, D., & Fairhead, J. (2016). Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative. *Frontiers in Ecology and the Environment*, *14*(2), 71–76. https://doi.org/10.1002/fee.1226

Sombroek, W. (1966). *Amazon soils. A reconnaissance of the soils of the Brazilian Amazon region*. Verslagen.

Steiner, C., Das, K. C., Melear, N., & Lakly, D. (2010). Reducing nitrogen loss during poultry litter composting using biochar. *Journal of Environment Quality*, *39*(4), 1236. https://doi.org/10.2134/jeq2009.0337

Steiner, C., Glaser, B., Geraldes Teixeira, W., Lehmann, J., Blum, W. E. H., & Zech, W. (2008). Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science*, *171*(6), 893–899. https://doi.org/10.1002/jpln.200625199

Tang, J., Zhu, W., Kookana, R., & Katayama, A. (2013). Characteristics of biochar and its application in remediation of contaminated soil. *Journal of Bioscience and Bioengineering*, *116*(6), 653–659. https://doi.org/10.1016/j.jbiosc.2013.05.035

Thomas, S. C., & Gale, N. (2015). Biochar and forest restoration: A review and meta-analysis of tree growth responses. *New Forests*, *46*(5–6), 931–946. https://doi.org/10.1007/s11056-015-9491-7

Verhoeven, E., Pereira, E., Decock, C., Suddick, E., Angst, T., & Six, J. (2017). Toward a better assessment of biochar-nitrous oxide mitigation potential at the field scale. *Journal of Environmental Quality*, *46*(2), 237–246. https://doi.org/10.2134/jeq2016.10.0396

Vithanage, M., Herath, I., Joseph, S., Bundschuh, J., Bolan, N., Ok, Y. S., Kirkham, M. B., & Rinklebe, J. (2017). Interaction of arsenic with biochar in soil and water: A critical review. *Carbon*, *113*, 219–230. https://doi.org/10.1016/J.CARBON.2016.11.032

von Liebig, J. (1878). *Chemische Briefe*. Verlag Wintersche.

Wang, H., Lee, S. J., Olarte, M. V., & Zacher, A. H. (2016). Bio-oil stabilization by hydrogenation over reduced metal catalysts at low temperatures. *ACS Sustainable Chemistry and Engineering*, *4*(10), 5533–5545. https://doi.org/10.1021/acssuschemeng.6b01270

Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy*, *8*(3), 512–523. https://doi.org/10.1111/gcbb.12266

Wang, T., Camps-Arbestain, M., Hedley, M., & Bishop, P. (2012). Predicting phosphorus bioavailability from high-ash biochars. *Plant and Soil*, *357*(1–2), 173–187. https://doi.org/10.1007/s11104-012-1131-9

Wardle, D. A., Nilsson, M., & Zackrisson, O. (2008). Fire-derived charcoal causes loss of forest humus. *Science (New York, N.Y.)*, *320*, 629. https://doi.org/10.1126/science.1154960

Weng, Z. H., Van Zwieten, L., Singh, B. P., Tavakkoli, E., Joseph, S., Macdonald, L. M., Rose, T. J., Rose, M. T., Kimber, S. W. L., Morris, S., Cozzolino, D., Araujo, J. R., Archanjo, B. S., & Cowie, A. (2017). Biochar built soil carbon over a decade by stabilizing rhizodeposits. *Nature Climate Change*, *7*(April), 371–376. https://doi.org/10.1038/nclimate3276

Werner, C., Schmidt, H.-P., Gerten, D., Lucht, W., & Kammann, C. (2018). Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °c. *Environmental Research Letters*, *13*(4), 044036–044050. https://doi.org/10.1088/1748-9326/aabb0e

Whitman, T., & Lehmann, J. (2015). A dual-isotope approach to allow conclusive partitioning between three sources. *Nature Communications*, *6*, 8708. https://doi.org/10.1038/ncomms9708

Whittaker, R. J. (2010). Meta-analyses and mega-mistakes: calling time on meta-analysis of the species richness–productivity relationship. *Ecology*, *91*(9), 2522–2533. https://doi.org/10.1890/08-0968.1

Wiedner, K., & Glaser, B. (2015). Traditional use of biochar. In J. Lehmann, & S. Joseph (Eds.), *BIochar for environmental management - science and technology*, 2nd ed (pp. 15–38) Routledge.

Wiedner, K., Schneeweiß, J., Dippold, M. A., & Glaser, B. (2015). Anthropogenic Dark Earth in Northern Germany — The nordic analogue to terra preta de Índio in Amazonia. *Catena*, *132*, 114–125. https://doi.org/10.1016/J.CATENA.2014.10.024

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56. https://doi.org/10.1038/ncomms1053

Xiang, Y., Deng, Q., Duan, H., & Guo, Y. (2017). Effects of biochar application on root traits: A meta-analysis. *GCB Bioenergy*, *9*(10), 1563–1572. https://doi.org/10.1111/gcbb.12449

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, *36*(1), 2–18. https://doi.org/10.1111/sum.12546

Yu, L., Yu, M., Lu, X., Tang, C., Liu, X., Brookes, P. C., & Xu, J. (2018). Combined application of biochar and nitrogen fertilizer benefits nitrogen retention in the rhizosphere of soybean by increasing microbial biomass but not altering microbial community structure. *Science of the Total Environment*, *640–641*, 1221–1230. https://doi.org/10.1016/j.scitotenv.2018.06.018

Zhang, L., Jing, Y., Xiang, Y., Zhang, R., & Lu, H. (2018). Responses of soil microbial community structure changes and activities to biochar addition: A meta-analysis. *Science of the Total Environment*, *643*, 926–935. https://doi.org/10.1016/J.SCITOTENV.2018.06.231

Zhang, L., Xiang, Y., Jing, Y., & Zhang, R. (2019). Biochar amendment effects on the activities of soil carbon, nitrogen, and phosphorus hydrolytic enzymes: A meta-analysis. *Environmental Science and Pollution Research*, *26*(22), 22990–23001. https://doi.org/10.1007/s11356-019-05604-1

Zhao, S., Schmidt, S., Qin, W., Li, J., Li, G., & Zhang, W. (2020). Towards the circular nitrogen economy – A global meta-analysis of composting technologies reveals much potential for mitigating nitrogen losses. *Science of the Total Environment*, *704*, 135401. https://doi.org/10.1016/J.SCITOTENV.2019.135401

Zheng, J., Han, J., Liu, Z., Xia, W., Zhang, X., Li, L., Liu, X., Bian, R., Cheng, K., Zheng, J., & Pan, G. (2017). Biochar compound fertilizer increases nitrogen productivity and economic benefits but decreases carbon emission of maize production. *Agriculture, Ecosystems & Environment*, *241*, 70–78. https://doi.org/10.1016/J.AGEE.2017.02.034

Zhou, H., Zhang, D., Wang, P., Liu, X., Cheng, K., Li, L., Zheng, J., Zhang, X., Zheng, J., Crowley, D., van Zwieten, L., & Pan, G. (2017). Changes in microbial biomass and the metabolic quotient with biochar addition to agricultural soils: A Meta-analysis. *Agriculture, Ecosystems and Environment*, *239*, 80–89. https://doi.org/10.1016/j.agee.2017.01.006.

Zimmerman, A. R., & Gao, B. (2013). The stability of biochar in the environment. In N. Ladygina, & F. Rineau (Eds.), *Biochar and soil biota* (pp. 1–40). Crc press.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the Supporting Information section.

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