Does biochar enhance soil organic matter formation in tropical soils?

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Abstract. Tropical soils are often deeply weathered and vulnerable to degradation. Biochar is a promising means to improve physico-chemical characteristics such as pH or bulk density. Sustainable soil amelioration is best achieved by improving biological activity, resulting in enhanced soil organic matter (SOM) stocks. In a meta-analysis, we investigated if biochar amendment to tropical soils led to native SOM stock increases. We found a mean additional C accumulation (MAC) of 0.29% soil dry weight (% dw). MAC was independent of study duration, climate, and biochar addition rate, but strongly linked to soil type and nutrient status prior to the experiment: In Nitisols, MAC was highest (0.99% dw) and initial C and N contents were higher in these soils. MAC was negative in Ferralsols and Oxisols (~0.01% dw and ~0.2% dw respectively). MAC as a percentage of initial C content was <50% for most soil types, but ~50% in Ferralsols, Oxisols and Ultisols. We conclude that while biochar can enhance SOM stocks, attention has to be paid to the soil environment it is amended to. In low-activity clay soils, biochar amendment can lead to C mining and should therefore be co-amended with nutrient-rich organic amendments.

1. Introduction

Half of the world’s population will live in tropical regions by 2050 [1] and therefore largely on the fruits that tropical soils are able to bear [2]. Sustainable, that is, soil conserving, amelioration of soil quality in tropical soils is therefore of pivotal importance.

Many of the tropical soils that are currently under culture are of a kaolinitic – halloysitic makeup [3]. These soils are characterised by high clay contents, often good drainage and low natural cation exchange capacity (CEC) <24 cmol, kg⁻¹ [4]. Additionally, they are very vulnerable to physical degradation brought about by inappropriate management practices such as excessive liming and deep tillage [5]. Soil degradation is always associated with a loss of soil organic matter (SOM). SOM resumes many functions, among which soil structural stability and provision of cation exchange sites are the primary physical and chemical characteristics that aid infiltrability, root penetrability, and nutrient retention. Moreover, SOM is “generated” by the activity of soil biota, whose diversity and function remains elusive still today. Hence, SOM rich soils display high taxonomic and functionally redundant biodiversity.

Seemingly against all probability, highly fertile, anthropogenic Dark Earths are found circumtropical on highly weathered kaolinitic parent material [6,7]. Amazonian Terra Preta soils have received a lot of scientific attention during the last two decades as to their genesis. Terra Preta and other anthropogenic Dark Earths display high contents both in SOM [6] and in pyrogenic C [8].
Shortly after their discovery, the term “biochar” was coined as it was believed to be the main “fertilising” amendment of Dark Earths [6] and sought to be produced as a soil amendment. Biochar is the product of incomplete combustion of biomass as a result of severe oxygen limitation during combustion. Although these Dark Earths are rich in pyrogenic C, their high SOM content and particularly their high biological activity cannot be explained by charcoal addition alone as charcoal is biologically quasi-inert, i.e. is degradable only to a small percentage due to its highly condensed nature [9,10]. Hence, the question arises if biochar, amended together with nutrient-rich substrates such as compost, can stimulate SOM accumulation in tropical soils.

The present study consists of two parts: Firstly, we quantitatively assess the accumulation of “extra” C in biochar-amended tropical soils in relation to other parameters such as pH and CEC. Secondly, we investigate possible mechanisms of biochar – SOM interactions from selected studies. Finally, we point out specific research topics to be explored in order to assess whether and, if so, how biochar can aid soil amelioration by stimulating natural SOM accumulation.

2. Materials and methods

2.1. Paper selection
We selected the papers for this review from a topic search Web of Science core collection up to the end of 2018, using the following keywords: biochar tropic*, biochar africa*, biochar savanna*, biochar oxisol*, biochar ultisol*, and biochar ferralsol*. Anthropogenic dark earths such as Terra preta, Terra mulata etc. are only discussed as far as they appeared under the given search terms, but not considered for the quantitative analyses as C dynamics are fundamentally different from biochar-amended soils. For defining the study area as tropical, the hard criterion of 23.5° latitude was applied. Furthermore, we considered studies that applied or investigated biochar or black carbon and measured C-related parameters, such as total C, TOC, CO₂ evolution or enzyme activities related to the breakdown of complex C substrates.

2.2. Quantitative analyses
Only soil types rendering n >3 observations in the final dataset were considered for the quantitative analyses. We maintained the mixed WRB/USDA nomenclature for soil taxonomy as not enough qualifiers were provided in the studies for safely converting USDA nomenclature into WRB nomenclature. From the biochar C content, we calculated the total amount of C that was amended. We compared the theoretically expected C content after biochar amendment with the measured C content. The difference between the two values was termed “mean additional C accumulation” (MAC) and assumed to be the amount of surplus C that was accumulated additionally to biochar C (Formula (1)).

\[
\text{MAC}(\text{dw}) = \text{C}_{\text{reported}}(\text{dw}) - \text{C}_{\text{expected}}(\text{dw})
\]

Where \(\text{C}_{\text{reported}}\) was the post-amendment soil C content taken from the literature and \(\text{C}_{\text{expected}}\) was calculated according to formulas (2) and (3) for studies providing gravimetric biochar application rates.

\[
\text{C}_{\text{expected}}(\text{soil dw}) = \text{C}_{\text{initial}}(\text{soil dw}) + \text{C}_{\text{amended}}(\text{soil dw})
\]

\[
\text{C}_{\text{amended}}(\text{soil dw}) = \left(\frac{\text{C}_{\text{biochar}}(\text{dw}) \times \text{application rate}(\text{t m}^{-3})}{\rho_{\text{bulksoil}}(\text{t m}^{-3})}\right)
\]

\(\text{C}_{\text{amended}}\) represents the portion of additional soil C content that was added by the biochar amendment alone, and \(\rho_{\text{bulksoil}}\) represents soil bulk density. If not specified in the study, we assumed a bulk density of 1.25 g cm⁻³, assuming compaction of mostly clay-rich soils as a result of cultivation. The depth of amendment was assumed to be 0.2 m, if not specified otherwise. Initial C content (\(\text{C}_{\text{initial}}\),}
biochar C content ($C_{\text{biochar}}$), and application rate were taken from the literature directly. For studies providing volumetric biochar application rates, formula (4) was used to calculate $C_{\text{amended}}$.

$$
C_{\text{amended}}(\text{soil dw}) = \frac{(C_{\text{biochar}}(\text{dw}) \cdot \text{application rate (vol.)})}{(\text{depth of amendment (m)} \cdot 10^4 \text{m}^2 \cdot \rho_{\text{bulk soil}}(t \cdot \text{m}^{-3}))}
$$ (4)

All statistical analyses were performed in the R environment using R version 3.2.3 [11]. GLM was used to test for differences between C accumulation in soil types and possible interactions between biochar and soil characteristics.

3. Results

We found 65 studies published between 2003 and 2018 that met our selection criteria. For the quantitative analyses, we considered 28 of these studies, representing 20 soil environments. We calculated an overall mean additional C accumulation (MAC) of 0.29% dw, corresponding to an overall median additional C accumulation of 0.21% dw. MAC was significantly influenced only by soil type and was higher in Nitisols (0.99% dw) compared to other soil types. In Ferralsols and Oxisols, MAC was slightly negative (~0.01% dw and ~0.2% dw respectively, see figure 1). Yet, due to high variation in the data, overall MAC was not significantly different from zero. MAC as percentage of initial C content, which is more meaningful in terms of a soil’s additional C accumulation capacity, did not significantly differ between soil types (see figure 2), nor was it related to relative C addition (biochar C added as percentage of initial C content). Conspicuously, Nitisols also displayed the highest initial C and N contents (see figures 3 and 4). Yet, overall MAC was correlated to neither initial C nor N content.

**Figure 1.** Mean additional C accumulation per soil type. Bold lines indicate means, boxes indicate 50% confidence interval, dashed lines with bars indicate 95% confidence intervals, and circles indicate outliers.
Figure 2. Relative additional C accumulation per soil type. Bold lines indicate means, boxes indicate 50% confidence interval, dashed lines with bars indicate 95% confidence intervals, and circles indicate outliers.

Figure 3. Initial soil C content per soil type. Bold lines indicate means, boxes indicate 50% confidence interval, dashed lines with bars indicate 95% confidence intervals, and circles indicate outliers.
4. Interaction of biochar and drivers of SOM dynamics

4.1. Interactions of biochar and microorganisms

Several studies measured CO$_2$ evolution from the bulk soil [12–19] and others targeted aerobic degradation of the biochar itself [9,20–23]. Biochar amendment led to an increase in soil respiration [12–18], even though the effect was transient in one case [19]. Biochar also had a liming effect leading to reduced Al bioavailability and enhanced microbial activity [12]. The degradation of biochar itself mostly resulted from volatile OM adhering to the biochar surface [20, 23]. Biochars produced at lower temperatures were more degradable than biochars produced at higher temperatures [9,21]. Overall, less than 10% of biochar C were mineralised [21,22]. Simarani et al. [25] and Halmi et al. [26] found that biochar and fertiliser led to an increase in C$_{org}$, but not in C$_{mic}$ (% C$_{org}$). Microbial C/N ratio decreased after biochar addition and even further when fertiliser was added. Neither cellulase or endoglucanase activities were influenced by biochar or fertiliser, but β-glucosidase, xylanase, urease, and phosphodiesterase activities were elevated when biochar and fertiliser were added. Abdulrahman et al. [24] found that microbial activity responded positively to biochar addition, but without differences between application rates or additional microbial inoculation. Urease activity was elevated at the lower biochar application rates, while phosphatase activity was elevated at an intermediate rate. Ouyang et al. [14] found higher activities of catalase, polyphenol oxidase, peroxidase, β-glucosidase, and dehydrogenase in soil receiving low-temperature dairy manure biochar. Biochars from artisanal production (traditional kiln or barrel) were rich in untransformed plant material, such as phenols, lignins, and aliphatic C monomers and such compounds. While acting as a potential substrate for microorganisms, can also inhibit microbial growth [20]. Camenzind et al. [7] observed higher phospholipid fatty acid (PLFA) abundance in African Dark Earths (AfDEs) than in adjacent soils. AfDEs also had a higher fungi/bacteria ratio than adjacent soils. Paz-ferreiro et al. [12] found that fungi/bacteria ratio and gram-positive/gram-negative bacteria ratio were higher in the biochar amended soils. Additionally, general fungal and arbuscular mycorrhizal (AM) fungi abundance increased after biochar amendment. Simarani et al. [25] found an increased bacterial abundance after biochar addition, but only without additional fertiliser. Halmi et al. [26] reported an increase in both
bacterial and fungal gene copy numbers following biochar amendment. Abdulrahman et al. [24] found increased bacteria and actinobacteria abundances after biochar addition, independent of application rate, while fungi profited only from intermediate application rates. Contrastingly, Pandian et al. [32] reported rate-dependent higher abundance of all, bacteria, actinobacteria, and fungi in a biochar-amended acidic soil in India. Gomez Germano et al. [31] found a higher diversity of aromatic ring-hydroxylating dioxygenases (ARHD) gene groups in biochar particles of an Amazonian Dark Earth (ADE) than in bulk soil. Moreover, species diversity was higher and rarefaction curves were steeper in the biochar particles than in surrounding soil. “Priming” describes a lasting community metabolic change following the single addition of substrate, e.g. glucose. Positive priming leads to a net decrease of C stocks, while negative priming is associated with C “conservation”. Keith et al. [34] observed a positive priming effect of labile organic matter (LOM) on native SOM and biochar C, while biochar addition had a negative priming effect on LOM. Fang et al. [35] added that mineralisation of aged SOM was increased by both biochar and LOM addition. C mineralisation from all sources increased at higher temperatures. Temperature sensitivity of C mineralisation was highest in the biochar, indicating high activation energies for biochar C mineralisation.

4.2. Influence of biochar on SOM properties

Major et al. [36] found that biochar amendment led to increased dissolved organic C (DOC) and particulate organic C (POC) leaching, with higher biochar C contributions in the upper 15 cm. Biochar addition decreased the DOC/POC ratio, indicating decreased overall solubility of SOC. The authors suggest bioturbation as the main cause for POC translocation into the profile as high earthworm and termite burrowing activities were observed in the biochar-amended plots. Lee et al. [38] observed that biochar addition improved water retention and reduced nitrate and ammonium leaching, with higher N retention at higher biochar application rates. It is likely that biochar adsorption and plant N uptake have interactively caused the reduced nutrient leaching. Eykelbosh et al. [37] reported that biochar addition to the top 10 cm led to an overall decrease of DOC export. Biochar amended soil retained more high molecular-weight humic substances, but no amino acids and no additional nitrate. Solomon et al. [39] reported differences in SOM functional group composition of Amazonian Dark Earths (ADEs) compared to adjacent soils. ADEs were richer in pyrogenic C, as well as di-O-alkyl C, O-aryl C, and carbonyl C, and contained less alkyl C, methoxyl C, and O-alkyl C, indicating a higher degree of microbial processing of SOM. Mao et al. [8] argued that the large relative proportion of carboxyl C observed in ADEs stems from substitution of polyaromatic pyrogenic structures, i.e. fungal breakdown of biochar. Deenik et al. [41] found several volatile phenolic compounds in pre-amendment biochar whose concentrations gradually decreased over an incubation period of 30 – 40 days. Bird et al. [9] detected a weight gain in biochar-amended mesh bags in an Australian Cambisol over the course of three years. The increase was more pronounced in biochars produced at higher temperature, and almost disappeared when litter and/or limestone were added. Litter addition also enhanced microbial colonisation of the biochars. Nguyen et al. [40] characterised biochar from a Kenyan Nitisols that had been amended with biochar 2 – 100 years prior to sampling. While C content decreased with time since amendment, the C/N ratio remained stable. After 100 years since deposition, biochar O concentrations were around 60% on the interior and exposed surfaces. Carboxyl C on the biochar surface augmented very fast from 3% to 7% within 5 years. Mineral depositions on the biochar surfaces were observed as well. FT-IR spectra additionally indicated microbial colonisation of biochar particles. Oliveira et al. [42] investigated soil particles from different Terra Mulata, Oxisols, and Ultisols in Brazil using different imaging techniques. They found a higher concentration of C-, Ca-, and P-based particles in the Terra Mulata soils compared to Oxisols and Ultisols. These particles were also closer to each other than in the other soils. Additionally, they detected a high degree of SOM oxidation. [43] investigated the formation of organomineral complexes in ADEs and Terra Mulata soils in Brazil. Humin C was mostly associated with Ca, Mg, and poorly crystalline Al and Fe oxides. Obia et al. [44] found that aggregate biochar C content was the most meaningful predictor for aggregate stability. Consistently, aggregate stability was linearly correlated with aggregate organic C.
content. The authors also found that coarser textured soils might require higher biochar doses than loamy soils to improve aggregate stability. Ngo et al. [45] investigated the effect of different organic amendments on C storage focusing on mineral-bound OM and carbohydrate signatures. The combined application of biochar and vermicompost lead to increases in both mineral-bound SOM and sugar contents. Co-amended with vermicompost, biochar addition resulted in a decrease in the C6/C5 sugar ratio, indicating a higher portion of plant-derived sugars.

5. Discussion

Our results indicate accumulation of extra C after biochar amendment only in certain soil types. MAC was highest in Nitisols which are the only soils in our selection that contain primary weatherable minerals and are considered “fertile” in an agronomic sense [4]. Such favourable conditions mostly come with high biological activity which is boosted by organic amendments so that more biomass C is stabilised in soil. While MAC was minute in an absolute sense, the capacity of healthy soils to accumulate extra C as percentage of the initial C stock was enormous. On the other hand, MAC was negative in Ferralsols and Oxisols. These soils represent maximum weathered scenarios with strongly acidic conditions and high concentrations of mobile Al all of which are associated with permanent negative surface charges. It is often advised that these soils be limed and amended in small portions multiple times as to allow chemical and biological conditions to re-equilibrate before the next amendment.

The qualitative observations from the many studies referenced here draw a more detailed picture. Throughout all studies and soil types, biochar amendment enhanced microbial activity and exoenzyme activity, demonstrating increased access to degradable substrate, depending on the specific OM quality. Biochar C itself was mostly degraded when volatiles were released shortly after the amendment. The positive effects are probably attributable to improved chemical conditions as explained above. Minute, yet very consistent shifts in microbial community composition were reported by several authors. These shifts include a higher fungi/bacteria ratio, a higher gram-positive/gram-negative bacteria ratio, and a higher bacterial diversity within biochar particles in historic anthropogenic Dark Earths. We hypothesise that bacteria profit from high availabilities of labile substrates shortly after the amendment of biochar and compost, manure or sludge and stabilise C and particularly N in bio- and necromass. Fungi take over after most of the labile substrate is consumed and further stabilise C and nutrients (partially from bacterial necromass) in their own biomass. Fungal thriving possibly invokes a cascade of reactions in the soil food web with higher grazing activities of fungivorous microarthropods, less root-feeding of opportunistic feeders, and the establishment of predatory soil fauna. The latter was observed by Danra et al. [46] who found increased Gamasina abundance and diversity in biochar-amended plots of a soil rehabilitation site in Cameroon. Microarthropod grazing further enhances fungal activity and results in more efficient substrate breakdown [47]. Higher bacterial diversity within biochar particles is a clear indication of habitat fragmentation, and thus “fungal highways” may play a more important role for bacterial mobility in biochar-amended soils under dry-rainy season climates. The changes in SOM composition in historic anthropogenic Dark Earths confirm this concept as they clearly demonstrate surface oxidation and microbial colonisation of biochar particles in soil. Both the results of the priming studies and on organomineral complexation demonstrate the stabilisation of SOM by biochar amendment over short (priming) and longer terms (organomineral complexes) and underline the necessity of co-amending biochar with labile substrate for lasting positive effects.

6. Recommendations for further research

We see a high need for systematic research on the interactions of soil type, soil texture, and mineralogy, with biochar-related phenomena. These include soil aggregation patterns, hydraulic conditions, but also chemical aspects such as Al bioavailability and surface charge distribution. While the quantitative trends that we found were consistent, statistical significance was not achieved, but would have been, had there been more quantitative studies available. Qualitative changes in SOM
composition and microbial activity were more pronounced and may be a more mechanistic target for unveiling biochar effects on tropical soils. In tropical soils, up to 95% of SOM is occluded within microaggregates via different mechanisms [48]. How does biochar interfere with these occlusion mechanisms? Soil fungi often produce strong organic acids with pH ~ 2 which have the ability to leach small nutritious compounds off mineral surfaces. How does biochar influence these acquisition mechanisms? Does biochar itself adsorb such compounds in a way that influences their availability to soil life? [50] recently pointed out that microbial biomass C and microbial turnover may be key in controlling soil C storage. Our results indicate that the microbial response to biochar amendment is group specific and follows a time line. What does this specific succession look like and are discrete phases discernible? How is the specific chronology with dominance of certain groups crucial to the agronomic success of biochar? If microbial groups are enhanced by biochar amendment, how, if at all, does this effect propagate in the food web? Mesocosm studies from temperate ecosystems show that microbial colonisation of biochar is crucial for “acceptance” by collembola [49]. In tropical regions with unimodal rainfall patterns, soil microarthropod dominance follows a seasonal pattern caused by vertical migratory activities with highest abundances in full rainy season [46]. Liang et al. [51] showed that biochar can increase the resilience of microbial communities to drought. Does biochar influence also the vertical migration patterns of soil fauna? And if there are interactions of biochar and the soil food web, how does this impact OM dynamics? Will it lead to C mining and diminished soil C stocks or does more efficient substrate breakdown result in more biomass and SOM stabilisation? While focusing on specialised sub-questions and microscale investigations, we must not lose sight of the bigger ecological picture that sets the frame in which our research is placed. Biochar-amended soil as a highly anisotropic medium may render completely different results when looked at in different scales. Therefore, spatially explicit methods will play a major role in elucidating how biochar is incorporated into aggregates and how lattice defects and mineral depositions influence interaction of the biochar surface with SOM and soil microorganisms. We encourage researchers to engage in this topic and to investigate effects of biochar on trophic interactions, with special sensitivity to possible bottom-up effects caused by altered microbiomes.

7. Conclusions
The good that biochar can do largely depends on the circumstances of its application. These include soil type and soil health prior to application. These consistent yet statistically insignificant trends indicate a lack of systematic data on biochar application to tropical soils. We have also shown that while quantitative changes in soil C content may be minute and hard to prove, qualitative changes in SOM quality and microbial activity may be more pronounced and useful in detecting biochar effects on tropical soils. In the long term, biochar amendment can only be successful, if it leads to more lively soils with higher SOM stocks that are able to produce high enough yields to support the world population and to buffer adverse effects of climate change. It is evident that a one-size-fits-all solution for biochar amendment does not exist. Sustainable soil amelioration must reflect the site-specific requirements and limitations. In highly weathered acidic soils this means applying small doses multiple times, while soils with more weatherable minerals may be more resilient and can possibly cope with higher amounts of amendments at the same time. The closely entwined problems detailed above show that the question if biochar enhances SOM formation is not one of soil science alone. Solving the puzzle if biochar is ultimately beneficial requires collaborative interdisciplinary effort.

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