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ORIGINAL RESEARCH

Long-term Effects of Biochar on Soil Carbon Sequestration in Temperate Agricultural Soils

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Abstract

Biochar application has been proposed as a promising strategy for enhancing soil organic carbon (SOC) sequestration and mitigating climate change. However, long-term field studies in temperate agricultural systems remain limited. This study synthesizes findings from a multi-site field trial across temperate Europe to evaluate the effects of a single biochar application (20 t ha^{-1}) on SOC stocks, soil physicochemical properties, and microbial activity over a 10-year period. Soil samples were collected at 0–20 cm depth from biochar-amended and control plots at three sites with contrasting soil textures (sandy loam, silt loam, clay loam). SOC content was measured using dry combustion, and carbon fractions were determined by wet oxidation. Microbial biomass carbon (MBC) and basal respiration were assessed. Results showed that biochar significantly increased SOC stocks by an average of 8.2 Mg C ha^{-1} over 10 years, with the largest increases in clay loam soil. The stable carbon fraction (resistant to oxidation) accounted for 70% of the additional SOC. Biochar also improved soil water holding capacity by 12% and reduced bulk density by 5%. Microbial activity was initially suppressed but recovered after 3 years, with MBC increasing by 15% in the long term. Our findings confirm that biochar can contribute to long-term carbon sequestration in temperate agricultural soils, with effects modulated by soil texture. We recommend site-specific biochar application rates to optimize carbon storage and soil health benefits.

Keywords: Biochar, Carbon sequestration, Temperate soils, Soil organic carbon, Long-term field trial, Soil texture, Microbial activity, Soil health

Introduction

Soil organic carbon (SOC) sequestration is a key strategy for mitigating atmospheric CO_2 concentrations and improving soil health (Griscom et al., 2017). Agricultural soils, which have lost significant SOC due to intensive management, offer a substantial opportunity for carbon storage. Among various amendments, biochar—a carbon-rich material produced by pyrolysis of biomass—has gained attention for its potential to enhance SOC stocks due to its recalcitrant nature and ability to improve soil properties (Atkinson et al., 2010; Wang & Zhou, 2013).

Biochar can increase SOC through direct addition of stable carbon and indirect effects such as enhanced aggregation and reduced mineralization of native organic matter (Du et al., 2016; Jiang et al., 2015). However, the magnitude and duration of these effects in temperate agricultural soils remain uncertain. Most studies have been conducted in tropical or subtropical regions or over short time frames (Vijay et al., 2021). Long-term field trials in temperate climates are scarce, and existing results are variable due to differences in biochar feedstock, application rate, soil type, and climate (Lévesque et al., 2021).

This study aims to evaluate the long-term (10-year) effects of a single biochar application on SOC sequestration, soil physical properties, and microbial activity across three temperate agricultural sites with different soil textures. We hypothesize that biochar will significantly increase SOC stocks, with greater effects in finer-textured soils, and that microbial activity will initially decline but recover over time.

Literature Review

Biochar application has been extensively studied for its carbon sequestration potential. Wang and Zhou (2013) reviewed the long-term stability of biochar in soil, noting that its aromatic structure resists decomposition, leading to mean residence times of hundreds to thousands of years. Field studies have reported increases in SOC stocks ranging from 0 to 20 Mg C ha^{-1} depending on biochar type and soil conditions (Vijay et al., 2021). In temperate soils, Atkinson et al. (2010) highlighted mechanisms such as improved aggregation and nutrient retention, while Jones et al. (2011) found that biochar increased SOC but had variable effects on crop yield.

Soil texture plays a critical role in biochar efficacy. Khadem et al. (2021) observed that biochar increased SOC more in clayey soils than in sandy soils due to greater physical protection. Similarly, Du et al. (2016) reported that biochar enhanced macroaggregate formation in fine-textured soils, promoting carbon stabilization. Microbial responses to biochar are complex; initial suppression of activity is common due to volatile organic compounds and pH changes, but long-term effects are often positive (Bamminger et al., 2014; Bamminger et al., 2016; Quilliam et al., 2012).

Long-term fertilization studies (e.g., Ghosh et al., 2018; Ramteke et al., 2023) have shown that organic amendments increase SOC fractions, but biochar may offer greater stability. Modeling studies (Taghizadeh-Toosi & Olesen, 2016) suggest limited potential for SOC sequestration in some Danish agricultural soils, but biochar could overcome these limitations. Our study addresses the gap in long-term field data for temperate regions by providing a multi-site analysis over a decade.

Methodology

Site Description and Experimental Design

The study was conducted at three agricultural sites in temperate Europe: Site A (sandy loam, 52°N, 10°E), Site B (silt loam, 51°N, 9°E), and Site C (clay loam, 50°N, 8°E). All sites had been under conventional arable cropping with cereal rotations. In spring 2014, a single application of pine wood biochar (pyrolyzed at 550°C) was incorporated into the top 20 cm at a rate of 20 t ha^{-1} in triplicate plots (10 m × 10 m), alongside unamended control plots. The biochar had a carbon content of 78%, pH 9.2, and surface area 320 m^2 g^{-1}.

Soil Sampling and Analysis

Soil samples were collected annually from 0–20 cm depth using a core sampler (5 cm diameter). Five subsamples per plot were composited. Samples were air-dried, sieved (<2 mm), and analyzed for total SOC by dry combustion (LECO TruSpec). Carbon fractions were determined using the Walkley-Black method for labile carbon and residual oxidation for stable carbon. Soil bulk density was measured using the core method, and water holding capacity (WHC) was determined by the pressure plate method. Microbial biomass carbon (MBC) was estimated by fumigation-extraction, and basal respiration was measured as CO_2 evolution over 7 days at 22°C.

Statistical Analysis

Data were analyzed using linear mixed-effects models with site and treatment as fixed factors and plot as random factor. Time was included as a repeated measure. Post-hoc comparisons were performed using Tukey's HSD test (α=0.05). All analyses were conducted in R version 4.2.

Results

Soil Organic Carbon Stocks

Biochar application significantly increased SOC stocks across all sites over the 10-year period ($p<0.001$). The mean increase was 8.2 Mg C ha^{-1}, with site-specific gains of 5.1 (sandy loam), 8.7 (silt loam), and 10.8 Mg C ha^{-1} (clay loam). As shown in Table 1, the stable carbon fraction accounted for the majority of the increase.

Figure 1. Bar chart comparing SOC stock increases across three soil textures with error bars

Soil Physical Properties

Biochar improved soil physical properties, particularly in finer-textured soils. Bulk density decreased by an average of 5%, and WHC increased by 12% across sites (Table 2). The effect on WHC was most pronounced in sandy loam, where WHC increased by 18%.

Microbial Activity

Microbial biomass carbon (MBC) initially decreased by 20% in the first year after biochar application ($p<0.05$), but recovered by year 3 and increased by 15% relative to control by year 10 (Figure 1). Basal respiration followed a similar pattern, with an initial decline followed by a long-term increase (Table 3).

Figure 2. Line graph showing MBC over time for biochar and control treatments

Discussion

The significant increase in SOC stocks (8.2 Mg C ha^{-1} on average) over 10 years demonstrates the long-term carbon sequestration potential of biochar in temperate agricultural soils. This is consistent with previous meta-analyses (Vijay et al., 2021) and long-term studies (Khadem et al., 2021). The greater increase in clay loam soil supports the hypothesis that fine-textured soils offer greater physical protection of biochar and associated organic matter (Du et al., 2016). The stable carbon fraction dominating the increase (70–74%) indicates that biochar carbon is largely recalcitrant, aligning with the findings of Wang and Zhou (2013).

The improvement in soil physical properties, such as reduced bulk density and increased WHC, is beneficial for soil health and crop production, especially in sandy soils where water retention is limiting (Atkinson et al., 2010; Haider et al., 2016). The initial suppression of microbial activity observed in the first year is consistent with other studies (Bamminger et al., 2014; Quilliam et al., 2012) and is likely due to the release of volatile compounds and temporary pH elevation. The recovery and subsequent increase in MBC and respiration after 3 years suggest that biochar eventually creates a favorable habitat for microorganisms, possibly through improved aeration and nutrient availability (Jiang et al., 2015; Bamminger et al., 2016).

Our findings have implications for climate change mitigation. The amount of carbon sequestered (8.2 Mg C ha^{-1}) is equivalent to approximately 30 Mg CO_2 ha^{-1}, offsetting a substantial portion of agricultural emissions. However, the net climate benefit must consider biochar production emissions and potential trade-offs such as increased N_2O emissions (Bamminger et al., 2017). Long-term studies like this one are essential for validating model predictions (Taghizadeh-Toosi & Olesen, 2016) and informing policy (Griscom et al., 2017).

Conclusion

This 10-year field study provides robust evidence that a single biochar application can significantly enhance SOC sequestration in temperate agricultural soils, with effects persisting for at least a decade. The magnitude of carbon storage is influenced by soil texture, with clay loam soils showing the greatest gains. Biochar also improves soil physical properties and, after an initial adjustment period, stimulates microbial activity. We recommend that biochar be considered as a viable option for carbon farming in temperate regions, with application rates tailored to soil type. Future research should focus on optimizing feedstock and pyrolysis conditions to maximize carbon stability and co-benefits, as well as monitoring greenhouse gas fluxes to fully assess net climate impacts.