Author(s): Jari Hyväluoma, Mika Tähtikarhu, Kimmo Rasa

Title: Biochar impacts on soil properties : A review focusing on Nordic research

Year: 2026

Version: Published version

Please cite the original version:

Hyväluoma, J., Tähtikarhu, M., & Rasa, K. (2026). Biochar impacts on soil properties - A review focusing on Nordic research. Agricultural and Food Science, 35(1), 37–50. https://doi.org/10.23986/afsci.164143 (Original work published 2026)

AGRICULTURAL AND FOOD SCIENCE

Agricultural and Food Science (2026) 35: xx–xx

https://doi.org/10.23986/afsci.164143

Biochar impacts on soil properties - A review focusing on Nordic research

Jari Hyväluoma, Mika Tähtikarhu, Kimmo Rasa

Natural Resources Institute Finland (Luke), Tietotie 4, FI-31600 Jokioinen, Finland
email: jari.hyvaluoma@luke.fi

Biochar used as a soil amendment has been reported to influence crop productivity and the environmental impacts of agriculture. The impacts are challenging to generalize, as they depend on regional farming and climatic conditions. We collected and synthesized the scattered research findings from Fennoscandian countries to increase understanding of biochar impacts (crop yield, soil hydraulic properties, soil structural stability and carbon storage) in high-latitude agricultural soils. The influence of biochar was generally minor, with only a few sporadic clearly positive indications. While the number of study cases was too small to draw indisputable conclusions, low-fertility soils could be potential targets for biochar in boreal conditions. Also, global meta-analyses show the greatest yield increases in coarse-textured, nutrient-poor and acidic soils. Such agricultural soils are, however, a minority in the Fennoscandian conditions, which calls for further systematic investigations on biochar application on non-arable soils. The synthesized experimental results indicate that biochar has the potential to increase the long-term soil carbon storage. Our review highlights the scarcity of long-term investigations into the effects of biochar ageing and consequently soil properties. Several field experiments set up over a decade ago could provide a sound basis for research focusing on biochar ageing.

Key words: soil amendment, soil hydraulic properties, aggregate stability, carbon storage, greenhouse-gas emissions

Introduction

Biochar is a carbonaceous material resulting from the thermal transformation of organic matter in an oxygen-limited environment inhibiting the combustion of the source material (Lehmann et al. 2006, Chen et al. 2019). Biochar has been a subject of great interest in soil science research over the past couple of decades due to its potential to promote long-term carbon storage in soils, enhance soil fertility, and facilitate environmental remediation (Ding et al. 2016, Oliveira et al. 2017, Lehmann et al. 2021). These applications are based on the distinct physicochemical properties of biochar which, when applied as a soil amendment, may improve the soil chemical, biological and physical characteristics. Biochar resembles charcoal, and these two materials are distinguished by their intended use. Charcoal is used as a fuel, whereas biochar is deliberately applied to soils for agricultural and environmental benefits, or applications other than fuel (Ok et al. 2016).

There are several techniques for biochar production including slow and fast pyrolysis, and hydrothermal carbonization (Kambo and Dutta 2015). The chars produced from these processes exhibit varying physicochemical properties, which can affect their potential applications (Kambo and Dutta 2015). Biochar is a product of a dry carbonization process, such as pyrolysis, where biomass is heated at elevated temperatures in the absence of oxygen (Amenaghawon et al. 2021). The char product resulting from hydrothermal carbonization (Ischia and Fiori 2021) is often coined as hydrochar results from a different treatment process and has both similarities and differences to pyrolysis biochar regarding its physicochemical properties (Cognigni et al. 2025). The feasibility of these methods depends notably on the moisture status of the used feedstock.

Biochar has many properties that have been found to benefit soil fertility and the environment (Beusch 2021). In biochar production, the organic matter in the original feedstock is transformed into a recalcitrant form that may persist in soil for hundreds or thousands of years, which promotes long-term carbon storage (Spokas 2010). Biochar is typically alkaline making it a suitable liming agent (van Zwieten et al. 2010). The high specific surface area, high cation exchange capacity and the positive and negative surface charges can lead to improved nutrient retention and reduced nutrient leaching (Beusch et al. 2019, Jindo et al. 2020). Biochar typically has high porosity, and the pore sizes are appropriate for water storage in plant-available form or can function as a habitat for microorganisms (Blanco-Canqui 2017, Edeh et al. 2020, Schnee et al. 2016). Biochar is typically nutrient-depleted, but for some nutrient-rich feedstocks, biochar can also contain substantial amounts of nutrients (Piash et al. 2021). Besides positive impacts, several studies have also reported neutral or adverse effects of biochar in the soil environment. For example, biochar can be a source of contaminants that can be naturally present in the feedstock or

Received 8 September 2025 / Accepted 22 January 2026
The Scientific Agricultural Society of Finland

produced during pyrolysis, or it can have negative effects on soil invertebrates (Brtnicky et al. 2021). Generally, biochar benefits are dependent on feedstock and processing temperature affecting biochar properties, application rate and particle size distribution, properties of soil receiving biochar, and climatic conditions among other factors (Blanco-Canqui 2021).

Plant production response of biochar soil amendments has been considered in several meta-analyses, which are partly based on overlapping data sources (Crane-Droesch et al. 2013, Liu et al. 2013, Jeffery et al. 2011, 2017, Awad et al. 2018, Dai et al. 2020, Ye et al. 2020, Bai et al. 2022). In general, typically positive yield effects due to biochar have been reported in these analyses and the grand mean (GM) increases in the yields have varied between 10% and 29%. However, a closer inspection reveals interesting details on how soil properties and climate affect the yield responses. Bai et al. (2022) (GM increase +25%) found that soil pH affected the yield response and biochar amendment was most beneficial for very acidic (pH<5) soils. The effect declined systematically for higher pH values, whereas yield increases did not vary significantly across different soil texture classes. In the meta-analysis of Crane-Droesch et al. (2013) (GM +10% estimated for application rate of 3 Mg ha^{-1}), low cation exchange capacity and low organic carbon content of receiving soil led to the greatest yield responses. Dai et al. (2020) (GM +16%) found that biochar improved plant growth in sandy and acidic soils and biochars with high ash content were found beneficial due to their fertilization effect. The meta-analysis by Jeffery et al. (2017) (GM +13%) showed that biochar increased yield only in the tropics (+25%) but not in temperate and boreal latitudes (–3%). They found that the yield effect was highest in soils with initially low pH and the effect systematically declined as initial soil pH increased. Importantly, Jeffery et al. (2017) emphasized that biochar yield effects observed in the tropics cannot be extrapolated to temperate regions. In an earlier meta-analysis, Jeffery et al. (2011) (GM +10%) reported the greatest positive yield effect in acidic or neutral soil and in course or medium textured soils. Liu et al. (2013) (GM +11%) found the greatest yield responses in acidic soils and sandy texture. Ye et al. (2020) (GM +29%) reported the greatest yield response for soils with sandy texture, low cation exchange capacity and in tropical or subtropical climates. Finally, Awad et al. (2020) (GM +18%), who considered only rice paddies, found the greatest effect in acidic soils with pH<5 and heavy textured soils. While these meta-analyses bring out partially different soil properties for which biochar amendment gives the highest yield responses, they contain some common observations. It appears that biochar amendment leads to positive yield responses especially in acidic soils with coarse texture and low cation exchange capacity. Therefore, yield increases are observed particularly in tropical soils, which typically have low pH and fertility, whereby the liming and fertilization effects likely are responsible for the detected yield effects. The arable soils in higher latitudes receive from their standard management practices commonly higher lime and fertilizer inputs, which reduces the benefits that can be achieved from biochar amendment.

Various aspects of biochar production and applications have been considered in a number of previous review articles. In their review, Xie et al. (2022) itemized 56 previous review articles concerning properties of biochar, production of biochar, or application of biochar. Some examples of recent review articles include Brtnicky et al. (2021) considering the adverse effects of biochar in the soil environment, Joseph et al. (2021) who reviewed the mechanisms controlling soil and plant responses to biochar, Lehmann et al. (2021) focusing on biochar in climate change mitigation, Schmidt et al. (2021) presenting a systematic review of global meta-analyses, and Xie et al. (2022) who summarized the impacts of feedstock and production process and reaction conditions on biochar properties.

Based on this background, the purpose of the present review is not to conduct another global review on biochar but instead concentrate on research conducted in the Fennoscandian countries focusing on biochar impacts on arable soils. As noted above, the results from different climates and soil properties cannot be straightforwardly generalized and extrapolated to other conditions, whereby the evaluation of biochar impacts needs to be based on conditions prevailing in each region. The purpose of this work is to collect and synthesize the scattered research findings from Finland, Norway and Sweden, which are mostly located in the boreal climate zone and thereby the environmental conditions differ from those of southern latitudes. This geographical scope limits the study to similar agricultural systems with comparable climatic and pedologic conditions. In addition to crop yield considered in the above-described meta-analyses, in this regional review, we focus on soil properties that potentially can be influenced by biochar amendment in the Fennoscandian conditions. The remainder of this article is organized as follows: In the next section, we shortly present how the literature for this study was selected. Then in the following sections, we review the published findings for crop yield, soil hydraulic properties, soil structural stability, carbon stocks, greenhouse-gas fluxes and biochar ageing. Finally, we summarize the observations and present an outlook for future research needs.

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https://doi.org/10.23986/afsci.164143

Material and methods

The data for this review was collected from and limited to peer-reviewed research publications. The literature search was performed in February 2025 using the Web of Science Core Collection database. The used keywords were "biochar AND soil (All Fields) and Sweden (Address)", and similarly for Norway and Finland. We thus assumed that the studies focusing on biochar soil impacts in these three countries had at least one author from the target region. The search resulted in 502 articles. The found literature was pre-screened and only those relevant to the focus of the present work were selected. Many of the search hits were studies on biochar effects in some other (mainly tropical) countries having co-authors from the three target countries and such articles were excluded from this study. Also, as our focus is on biochar soil impacts, we excluded papers concerning solely technical applications, biochar production, life-cycle assessment and economic analyses. The number of studies that passed the pre-screening was 110, which were thoroughly scrutinized. Finally, 40 articles were utilized in the subsequent sections. While the main focus of this work is on arable soil, we nevertheless also considered selected forestry and growing media-related works, when they provided additional insight into the topic.

The reviewed studies include field, pot and laboratory experiments. While soils in all study types are from the target area, other conditions in these study types coincide with the boreal conditions to various degrees. Field experiments are conducted in a natural setting, thus matching the environmental condition in the geographical area, whereas laboratory-packed samples are typically incubated in deviant conditions. Regarding the biochar field experiments, some of the experimental sites have been used in several individual studies at different times. Therefore, the experimental sites used in the reviewed articles are collected as Table 1, with references to studies where the site has been used.

Table 1. Experimental sites considered in this review at (a) agricultural land and (b) forest

Experimental site	Biochar type	Application rate (Mg ha^{-1})	Soil texture	Established	References
(a) Agriculture					
Southern Finland	Birch	9	Silt loam	May 2009	Karhu et al. 2011
Viikki-1, Finland	Spruce+pine	5 / 10	Sandy clay loam	May 2010	Tammeorg et al. 2014a, Kalu et al. 2021a, Kalu et al. 2022
Viikki-2, Finland	Spruce	5 / 10 / 20 / 30	Loamy sand	May 2011	Tammeorg et al. 2014b, Kalu et al. 2021a, Kalu et al. 2022
Ås, Norway	Miscanthus	11.4 / 35	Silty clay loam	September 2010	O'Toole et al. 2018, Rasse et al. 2017
Jokioinen, Finland	Forest residue	30	Clay	October 2016	Soinne et al. 2020, Kalu et al. 2022
Sarheim, Norway	Wood	28.7	Sandy loam / Coarse sand	September 2016	Persson et al. 2020
Parainen, Finland	Spruce, Willow	21 (spruce), 33 (willow)	Clay	September 2016	Karhu et al. 2021, Kalu et al. 2022, Kulmala et al. 2022, Peltokangas et al. 2023
(b) Forest					
Juupajoki, Finland	Spruce	5 / 10	Coarse sand	May 2015	Palviainen et al. 2020
Svartberget, Sweden	Pine	10	Fine sand	October 2011	Grau-Andrés et al. 2021

Results

Crop yield

The effects of biochar on crop yield have been considered in several studies. Some of the studies have been conducted as field experiments and some as pot experiments. Nine publications reported results of field experiments and Table 2 compiles their results. However, it is worthwhile to note that some publications which are referred to in Table 2 report results of the same field experiments (cf. Table 1), for example, from different time periods. In summary, the field experiments almost exclusively showed no yield effect of biochar application irrespective of the biochar type, application rate, soil type, or grown plant. The only exception is the paper by Kalu et al. (2022) which considered four Finnish biochar field experiments for one year and found a positive yield effect on two sites.

Interestingly, both sites had been considered in earlier studies where no yield increase was reported (Tammeorg et al. 2014b, Karhu et al. 2021), which suggests that weather conditions or biochar ageing may cause temporal variation in the soil impacts of biochar. One of the fields with a positive yield effect was Viikki-2 (Table 1). This field has a coarse-textured soil, which Kalu et al. (2022) presented as a plausible explanation for the observed yield effect during the extremely dry study year.

Table 3 summarizes the studies based on pot experiments. Only four pot experiment studies were found, two of which considered wood-based biochar (Saarnio et al. 2013, Kalu et al. 2021b) and two fertilization effects of broiler manure biochar (Keskinen et al. 2020, Sarvi et al. 2021). The results of these pot experiments were in line with the field experiments and mainly showed no yield effect due to biochar addition. Saarnio et al. (2013) found a positive yield effect in the first of the three timothy harvests, but the following harvests or total biomass production did not show differences between biochar and control treatments. The study of Kalu et al. (2021b) showed a positive yield effect at the higher application rate considered (5 weight-%) but not at the lower (1 weight-%). The studies concerning pyrolysed broiler manure showed the absence of the N fertilization effect of broiler manure biochar (Keskinen et al. 2020) and lowered yield due to lowered P fertilization effect resulting from pyrolysis of broiler manure (Sarvi et al. 2021).

Concerning the forest soils (Table 4), biochar addition has been found to have scattered effects on tree seedling growth in pot experiments (Pluchon et al. 2014, Eskandari et al. 2019, Köster et al. 2021). It should be noted that in the nursery production of tree seedlings, the purpose of biochar use is to reduce peat use with negative climate impact, whereby the question typically is whether biochar can be used as a peat additive without reducing the seedling performance (e.g. Köster et al. 2021). The field experiment by Palviainen et al. (2020) showed an increase in the average absolute tree height and diameter growth in nutrient-poor, xeric and course-textured forest soil even though all observations were not statistically significant. Grau-Andrés et al. (2021) found that biochar significantly increased the stem diameter and height of pine trees in fine sandy forest soil. The forest soil properties differ from the more fertile arable soils considered in the field experiments and resemble more the soils for which positive yield effects have been observed in meta-analyses (see Introduction).

Table 2. Yield results of field experiments. The experimental site is given in the Comments column (cf. Table 1).

Biochar type	Application rate (Mg ha^{-1})	Soil texture	Duration (yr)	Plant	Effect	Comments	Reference
Spruce+pine	5/10	Sandy clay loam	3 (2010–2012)	wheat / turnit rape / faba bean	0	Viikki-1; BC had no significant effects on grain yield or biomass production.	Tammeorg et al. 2014a
Spruce	5 / 10 / 20 / 30	Loamy sand	2 (2011–2012)	Wheat	0	Viikki-2; BC had no significant effect on the grain yield or quality.	Tammeorg et al. 2014b
Miscanthus straw	11.4 / 35	Silty clay loam	4 (2011–2014)	Oats / Barley	0	Ås; BC had no significant effect on grain or straw yield.	O'Toole et al. 2018
Forest residues	30	Clay	2 (2017–2018)	Oats	0	Jokioinen; BC had no effect on grain yield.	Soinne et al. 2020
Wood	28.7	Sandy loam / Coarse sand	3 (2017–2019)	Timothy / tall fescue	0	Sarheim; BC did not affect grass yield.	Persson et al. 2020
Willow / Spruce	33(willow) / 21(spruce)	Clay	1 (2017)	Wheat	0	Parainen; BC had no effect on grain yield.	Karhu et al. 2021
Spruce+pine	5 / 10	Sandy clay loam	8 (2010–2017)	Varying	0	Viikki-1; The experiment of Tammeorg et al. (2014a); BC had no significant effects (some exceptions).	Kalu et al. 2021a
Spruce	5 / 10 / 20 / 30	Loamy sand	8 (2011–2018)	Varying	0	Viikki-2; BC had no significant yield effects.	Kalu et al. 2021a
Forest Residue	30	Clay	1 (2018)	Oats	0	Jokioinen; No significant effect on crop yield.	Kalu et al. 2022
Willow / Spruce	33(willow) / 21(spruce)	Clay	1 (2018)	Oats	0/+	Parainen; Positive effect on grain yield for spruce BC; No significant difference for willow BC.	Kalu et al. 2022
Spruce+pine	10	Sandy clay loam	1 (2018)	Barley	0	Viikki-1; No significant effect on crop yield.	Kalu et al. 2022
Spruce	30	Loamy sand	1 (2018)	Barley	+	Viikki-2; Positive effect on grain yield.	Kalu et al. 2022

BC = biochar

https://doi.org/10.23986/afsci.164143

Table 3. Yield results of pot experiments

Biochar type	Application rate	Soil texture	Duration (yr)	Plant	Effect	Comments	Reference
Spruce	10 Mg ha^{-1}	Sandy till	1 (3 harvests)	Timothy	0	1st harvest: BC increased biomass production significantly. No significant effect in 2nd and 3rd harvests.	Saarnio et al. 2013
Broiler manure	-	Sand	1 (3 harvests)	Ryegrass	0	N fertilization experiment. No N fertilizer effect was found for pyrolysed broiler manure.	Keskinen et al. 2020
Hardwood	1 / 5 % (w/w)	Sandy loam	1 (1 harvest)	Ryegrass	0/+	1% BC treatment had no effect; 5% treatment significantly increased above-ground biomass.	Kalu et al. 2021b
Broiler Manure	-	Sand	1 (4 harvests)	Ryegrass	0	P fertilization experiment. Pyrolysis of broiler manure lowered the yield due to reduced fertilization effect.	Sarvi et al. 2021

BC = biochar

Table 4. Growth result of field and pot experiments using forest soil

Biochar type	Application rate	Soil texture	Duration (yr)	Plant	Effect	Comments	Reference
Wood (9 types)	3	-	11	Tree seedlings (4 species)	0/+	Pot experiment. BC had either neutral or positive effect on seedling growth depending on BC type, soil properties and plant species.	Pluchon et al. 2014
Paper mill sludge (HTC)	10 / 20% (v/v)	Peat	1	Pine seedlings	0/+	Pot experiment. Hydrochar application had either positive or neutral effects.	Eskandari et al. 2019
Spruce	5 / 10	Coarse sand	3 (2015–2017)	Pine	+	Field experiment. BC increased the average absolute tree height and diameter growth; all results were not statistically significant.	Palviainen et al. 2020
Pine	10	Fine sand	1 (2020)	Pine	+	Field experiment. BC significantly increased tree stem diameter and height.	Grau-Andrés et al. 2021
Willow	5 / 10 / 20 % (v/v)	Peat	1	Pine, spruce, birch seedlings	0	Pot experiment. Scattered effects.	Köster et al. 2021

BC = biochar, HTC = hydrothermal carbonization

Soil hydraulic properties

Soil water retention properties were considered in 20 articles. Some of the studies were based on soil samplings performed at biochar field experiments, where the biochar had aged and interacted with the soil. Part of the studies, in turn, were done with laboratory-packed samples where the soil and biochar were mixed in the laboratory before the water retention measurements. Also, the methodology varied greatly and thereof the results between the studies are partly incompatible. The most accurate studies were based on the measurement of the soil moisture characteristics curve, where the relationship between the soil water content and matric potential is determined. Most of these studies were done with characterization based on the hanging water column (sandbox) and/or pressure plate extractor methods, either with undisturbed samples taken from field sites (e.g. Tammeorg et al. 2014a) or laboratory-packed samples (e.g. Turunen et al. 2020). Only one study used an evaporation method (O'Toole et al. 2018). A large fraction of studies used simpler methods, with water-holding capacity determined using drainage methods (e.g. the funnel method), where a disturbed soil is wetted and then the excess water is allowed to drain. The water remaining in the sample is defined as soil water holding capacity (e.g. Karhu et al. 2011). The latter approach can be problematic in biochar studies as the bulk densities of soil and biochar are dissimilar, and the method is based on gravimetric moisture content.

Table 5 summarizes the studies based on field samples and the main impact found on soil water retention. In most of the studies, no significant effect due to biochar amendment was observed. The exceptions were the study of Karhu et al. (2011) and Kulmala et al. (2022). The former reported an 11% increase in water holding capacity for a silt loam due to biochar amendment determined with the funnel method. The latter study considered clay soil amended with two different biochar types (spruce and willow) and the plant available water determined from the soil moisture characteristics curve. Kulmala et al. (2022) reported a 16% increase for spruce biochar whereas the observed 11% increase for willow biochar was not statistically significant. In addition to the studies summarized in Table 5, we mention the field experiment by Zhao et al. (2019), where water contents at well-defined matric potentials were not measured, but water contents determined from soil samples suggested that biochar improved water retention on a coarse-textured forest soil.

Table 5. Water retention results based on soil samples from field experiments. The experimental site is given in the Comments column (cf. Table 1).

Biochar type	Application rate (Mg ha^{-1})	Soil texture	Method	Effect	Comments	Reference
Birch	9	Silt loam	Funnel	+	Southern Finland; BC increased WHC by 11%	Karhu et al. 2011
Spruce+pine	5 / 10	Sandy clay loam	Sandbox, pressure plate	0	Viikki-1; No statistically significant effect	Tammeorg et al. 2014a
Spruce	5 / 10 / 20 / 30	Loamy sand	Sandbox, pressure plate	(+)	Viikki-2; Only the highest application rate increased PAW in the first study year. No significant effects in the next year.	Tammeorg et al. 2014b
Miscanthus straw	11.4 / 35	Silty clay loam	Evaporation	0	Ås; No statistically significant differences between the treatments for PAW	O'Toole et al. 2018
Forest residue	30	Clay	Pressure plate, osmotic	0	Jokioinen; No statistically significant effect (BC increased water retention up to the suction of 25 kPa at p<0.1 level)	Soinne et al. 2020
Spruce+pine	10 / 30	Sandy clay loam / loamy sand	Sandbox, pressure plate	0	Viikki-1 and Viikki-2; BC had no effect on water retention (previous effects (Tammeorg 2014b) had disappeared).	Kalu et al. 2021a
Willow / spruce	33.4 (willow) / 20.6 (spruce)	Clay	Sandbox, pressure plate	+	Parainen; Spruce BC led to 16% higher PAW. (Willow BC increased PAW by 10%, but this increase was not statistically significant.)	Kulmala et al. 2022
Willow / spruce	22 (willow) / 20 (spruce)	Clay	Sandbox, pressure plate; Funnel	0	Parainen; No significant differences were observed in WHC (funnel). No significant difference in PSD derived from water retention curves.	Peltokangas et al. 2023

BC = biochar; WHC = water holding capacity; PAW = plant-available water; PSD = pore-size distribution

Table 6 summarizes the 12 studies using laboratory-packed samples with biochar mixed with soil. Also in these works, mixed results were reported. No biochar effect was reported in 6 articles. Hagner et al. (2016) used the funnel method and reported that biochar had a clear effect on water water-holding capacity of a sandy silt which increased from ca. 26% in control without biochar to ca. 36% in the biochar treatment with the highest application rate that was used (10 weight-%). Zhelezova et al. (2017) reported no effect for biochar addition to clay soil but for sand water holding capacity increased from 27% (control) to 42% (biochar addition of 30 weight-%). Results of both Hagner et al. (2016) and Zhelezova et al. (2017) showed a systematic increase in water holding capacity for increasing biochar application rate. These studies imply that the biochar dose is an important parameter in soils with water retention responding positively to biochar addition. Rasa et al. (2018) determined water retention curve for a clay soil amended with willow biochar (application rate 5 weight-%). They found that biochar influenced the soil moisture characteristics on the whole range of matric potentials. The impact was clearest in the wet end in two distinct pore size regimes, which Rasa et al. (2018) linked to the bimodal pore size distribution of the willow biochar which was imaged and quantified with X-ray tomography (see also Hyväluoma et al. 2018a, 2018b). Biochar also significantly increased the plant-available water in the soil. Heikkinen et al. (2019) measured the moisture of clay soil amended with 10 different biochars differing by the feedstock and processing method. They reported that slow pyrolysis biochars increased the water content at field capacity whereas some hydrochars had a negative effect probably due to their hydrophobicity. A negative impact on water retention was also reported by Köster et al. (2021), who amended peat growing media with willow biochar. The water-holding capacity of raw peat was higher than that of the used biochar, which explains the observed reduction. Turunen et al. (2020) studied sphagnum moss growing media amended with three different biochars and found statistically significant moisture differences in some matric potentials.

Soil hydraulic conductivity was considered only in one article, where the effect of biochar on the near-saturated hydraulic conductivity was measured in a clay field with tension infiltrometry (Soinne et al. 2020). In that study, the biochar treatment (forest residue biochar with an application rate of 30 Mg ha^{-1}) did not affect the hydraulic conductivity at any supply pressure heads considered (–1, –3 and –6 cm).

Table 6. Water retention results based on laboratory-packed soil-biochar samples

Biochar type	Application rate	Soil texture	Method	Effect	Comments	Reference
Activated char, household charcoal	2 / 4 % (w/w)	Sand	Drainage	0	BC had no effect on WHC.	Carlsson et al. 2012
Wheat residues	1 % (w/w)	Heavy clay / loam	Not reported	0	Only wet end considered (suctions 0, 0.1 and 1 m). BC had no effect on soil water content at these suctions.	Larsbo et al. 2013
Spruce	10 t ha^{-1}	Sandy till	Funnel	0	BC had no statistically significant effect.	Saarnio et al. 2013
Birch	ca. 2–10 % (w/w)	Sandy silt	Funnel	0	BC had a clearly positive effect on WHC.	Hagner et al. 2016
Wood mix	1 /10 / 20 / 30 % (w/w)	Clay / sand	Drainage	0/+ (clay / sand)	BC increased WHC of sandy soil. WHC had a strong positive correlation with BC application rate.	Zhelezova et al. 2017
Willow	5 % (w/w)	Clay, sand	Sandbox, pressure plate, osmotic	+	BC influenced soil moisture characteristics over the whole range of matric potentials and increased water content at FC, decreased at PWP.	Rasa et al. 2018
Various feedstock and processing methods (10 chars)	2 % (w/w)	Clay	Sandbox	+/-	Only field capacity is considered. SP BC increased water content, some HTC char had opposite effect due to their hydrophobicity.	Heikkinen et al. 2019
Willow, hemp hurd, mixed wood	10 % (v/v)	*Sphangnum* moss	Sandbox, pressure plate, osmotic	(+)	Moisture contents in the moss material differed from one or several of the amended materials in the lowest suction pressure of 0.2 kPa as well as in 39-310 kPa.	Turunen et al. 2020
Wood	28.7 t ha^{-1}	Sandy loam / coarse sand	Funnel	0	BC had no significant effect on WHC.	Persson et al. 2020
Willow	5 / 10 / 20 % (v/v)	Peat	Pressure plate	-	WHC of peat was much higher than that of biochar. BC addition decreased the water retention of the growing media.	Köster et al. 2021
Waste-water sludge	10 % (v/v)	Clay / sand / mull	Sandbox, pressure plate, osmotic	0	Some minor water retention impacts. Impacts on PAW were not statistically significant.	Turunen et al. 2021
Pine bark, spruce	10 / 30 t ha^{-1}	Peat	Funnel	0	WHC did not differ significantly between treatments.	Saarnio et al. 2024

BC = biochar; HTC = hydrothermal carbonization; SP = slow pyrolysis; WHC = water holding capacity; PAW = plant-available water

Soil structural stability

The impacts of biochar on soil structural stability were considered in four articles summarized in Table 7. Two of the articles considered soil aggregate stability of laboratory-incubated soil-biochar mixtures (Soinne et al. 2014, Heikkinen et al. 2019), whereas two considered soil samples collected from field experiments with biochar treatments (O'Toole et al. 2018, Soinne et al. 2020). In all four studies, wet-sieving methodology was used to determine the stability of aggregates. Soinne et al. (2020) also performed rainfall simulations using undisturbed soil columns taken from a field experiment.

The results in these studies are partly inconsistent. Soinne et al. (2014) reported that biochar increased the share of water-stable aggregates and decreased the turbidity, and the amount of small-sized soil particles released during wet-sieving. The three other studies showed no significant effects of biochar similarly to the rainfall simulation experiments by Soinne et al. (2020). However, some hydrochars considered by Heikkinen et al. (2019) resulted in improved aggregate stability, which likely resulted from the hydrophobicity of these materials.

Table 7. Effect of biochar on soil structure stability. The experimental site is given in the Comments column (cf. Table 1; Heikkinen et al. (2019) was based on laboratory samples).

Biochar type	Application rate	Soil texture	Experiment type	Method	Effect	Comments	Reference
Spruce+pine mix	0 / 15 / 30 Mg ha^{-1}	Clay, silty clay loam	Lab	Wet sieving	+	Jokioinen; BC increased aggregate stability and decreased colloid detachment	Soinne et al. (2014)
Miscanthus	11.4 / 35 Mg ha^{-1}	Silty clay loam	Field	Wet sieving	0	Ås; BC had no significant effect on aggregate stability	O'Toole et al. (2018)
Various feedstock and processing methods (10 chars)	2 % (w/w)	Clay	Lab	Wet sieving	+/0	Some HTC BCs increased aggregate stability and decreased colloid detachment significantly. SP BCs showed no significant differences to control.	Heikkinen et al. (2019)
Forest residue	30 Mg ha^{-1}	Clay	Field	Wet sieving, rainfall simulation	0	Jokioinen; BC did not increase aggregate stability (similar results from wet sieving and rainfall simulation)	Soinne et al. (2020)

BC = biochar, HTC = hydrothermal carbonization, SP = slow pyrolysis

Carbon stocks and greenhouse-gas fluxes

In addition to improving the soil growth conditions and crop yield, one aim of biochar addition is to increase the long-term carbon storage in soil due to the recalcitrant nature of biochar. The influence of biochar additions on carbon storage has been considered in a few Nordic studies. However, all these investigations have only considered short-term effects a couple of years after biochar amendment.

Tammeorg et al. (2014a) conducted a field experiment on sandy clay loam treated with spruce biochar with application levels of 5 and 10 Mg ha^{-1}. The topmost 20 cm layer was sampled and analysed one and two years after the application. They reported a statistically significant increase in the total carbon content for the higher application rate whereas the lower rate did not lead to a significant increase. After the first growing season, all added biochar was detected in the topsoil but after the third growing season, a –30 % decrease in the higher application rate was reported. In another field experiment on loamy sand, Tammeorg et al. (2014b) considered several application rates between 5 and 30 Mg ha^{-1} of spruce biochar. They found that biochar addition led to a statistically significant increase in the topsoil (20 cm) carbon content only when the application rate was sufficiently high (at least 20 Mg ha^{-1}). In the second year after application, only 18 % of the biochar-added carbon was detected. Tammeorg and coworkers linked the decrease in the recovered carbon to the horizontal transfer of biochar due to tillage operations and the downward movement of the biochar particles.

The field experiment of Soinne et al. (2020) was established on clay soil and treated with forest residue biochar using an application level of 30 Mg ha^{-1} and mixed to a depth of 10–12 cm. In this study, soil sampling was performed in four layers up to 45 cm depth. After one and half years, the soil carbon content in the shallow cultivated soil had significantly increased only in the topmost 10 cm layer compared to the control treatment. In the whole 45-cm soil profile, 79% of the added carbon was found. Decomposition, leaching and migration due to cultivation practices were mentioned as possible explanations for the loss of carbon added as biochar.

Peltokangas et al. (2023) analysed carbon content and storage in a field experiment on clay soil, where two different biochar types were considered (willow and spruce with total C inputs of 18 and 19 Mg ha^{-1}, respectively). In the soil sampling performed two years after the biochar addition, the recovery rates for the willow and spruce biochar were 46% and 61%, respectively. Peltokangas et al. (2023) attributed the losses to biochar translocation by tillage operations and burial due to biological processes.

Rasse et al. (2017) considered the stability of biochar produced of Miscanthus biomass in a field experiment established on a clay loam field. The experiment had two application rates leading to 8 and 25 Mg ha^{-1} addition of carbon to soil. Their study did not include results based on soil sampling. However, CO_2 fluxes were measured in two growing seasons after the application and isotopic ^{13}C composition in the second growing season. Based on these measurements authors estimated a mineralization rate of 0.8% per year and extrapolated a mean residence time higher than 100 years for the studied biochar in the field conditions.

Fluxes of CO_2, N_2O and CH_4 from biochar field experiments have been reported in some other studies as well (see Table 8). Generally, these studies have reported only occasionally statistically significant effects of biochar treatment. Karhu et al. (2011) reported that biochar increased the CH_4 uptake. The measurements at four field experiments considered by Kalu et al. (2022) showed some tendency of biochar to increase CO_2 fluxes. Kalu et al. (2021a) reported a statistically significant one-third reduction of N_2O flux in spring after sowing on one of the two studied experiments in one of the two measurement years. Kulmala et al. (2022), in turn, did not report statistically significant effects.

Table 8. Effect of biochar on the greenhouse-gas fluxes measured from field experiments

Biochar type	Application rate (Mg ha^{-1})	Soil texture	Effect on CO_2	Effect on N_2O	Effect on CH_4	Comments	Reference
Birch	9	Silt loam	0	0	-	Southern Finland; BC increased CH_4 uptake. No significant difference in CO_2 and N_2O	Karhu et al. 2011
Miscanthus	8 / 25 Mg C ha^{-1}	Clay loam	0	NR	NR	Ås; Cumulative CO_2 fluxes were not significantly affected by BC.	Rasse et al. 2017
Spruce+pine	5 / 10	Sandy clay loam	0	0	0	Viikki-1; BC had no effect on GHG emissions	Kalu et al. 2021a
Spruce	5 / 10 / 20 / 30	Loamy sand	0	(-)	0	Viikki-2; A two-year study, where a significant reduction on N_2O flux after sowing was observed in one spring.	Kalu et al. 2021a
Spruce / willow	21 (spruce) / 33 (willow)	Clay	(+)	0	0	Parainen; BC had no significant effect on cumulative GHC emissions. Spruce BC increased average CO_2 flux.	Kalu et al. 2022
Forest residues	30	Clay	0	0	0	Jokioinen; BC had no significant effect on cumulative GHC emissions.	Kalu et al. 2022
Spruce+pine	5 / 10	Sandy clay loam	0	0	0	Viikki-1; BC had no significant effect on cumulative GHC emissions.	Kalu et al. 2022
Spruce	5 / 10 / 20 / 30	Loamy sand	(+)	0	0	Viikki-2; BC had no significant effect on cumulative GHC emissions. BC increased average CO_2 flux.	Kalu et al. 2022
Spruce / willow	21 / 33	Clay	0	0	0	Parainen; BC had no significant effect on cumulative GHC emissions.	Kulmala et al. 2022

BC=biochar; GHC = greenhouse gas; NR = not reported

Biochar ageing

The studies considered above are mainly quite short-term, whereby the added biochar interacted with the soil and environment only for some years. However, biochar's chemical and physical properties may alter due to environmental exposure. Thus, the studies give limited information on the ageing processes and effects, despite that some studies were based on the same field experiments at different times (e.g. Tammeorg et al. 2014a, Kalu et al. 2021a, 2022). Two studies focused on biochar ageing in boreal forest soil. While forest soils differ in many aspects from arable soils, these studies can give some indications of the ageing processes also in arable soil.

Gao et al. (2017) field-incubated pyrolysed pine wood for 20 months in spodosol soil. They found that environmental exposure led to changes in the biochar density and porosity. The changes were dependent on the vertical placement, such that the porosity of above-ground biochar increased whereas in soil the opposite change was detected. However, environmental exposure did not result in large shifts in these properties. These authors discussed possible mechanisms behind the changes including particle breakage due to freeze-thaw cycles and particle infill by organic matter and soil minerals.

Hyväluoma et al. (2023), in turn, utilized a chronosequence of prescribed burning sites where the pyrogenic char formed in the forest burnings had been exposed to boreal environmental conditions for 1–71 years. These sites allowed studying long-term changes in pyrogenic char formed in the burnings. They found that char had retained its pore structure that originates from the wood cellular structure. Ageing had led to formation of fractures, surface coatings and pore fillings, which may alter the pore size distribution and accessibility of the pores. Also, changes in elemental composition were observed and this chronosequence suggested that these changes occur on a decadal time scale.

https://doi.org/10.23986/afsci.164143

Concluding discussion and future perspectives

The purpose of this work was to gather and synthetize research focusing on the effects of biochar on agricultural production in boreal climatic conditions based on research carried out in Finland, Norway and Sweden. Our focus was on the crop yield, soil hydraulic properties, soil structural stability and carbon storage results. Based on the literature reviewed, the influence of biochar on the studied soil properties is generally minor, with only a few sporadic positive indications. Considering plant growth and production, on agricultural soils both field and pot experiments showed mainly non-existent biochar influence. The few studies considering forest soils alluded to more positive biochar impacts. While the number of forest soil studies was too small to draw any definite conclusions, these findings could indicate that in boreal conditions the less fertile soils could be potential targets for biochar application. For example, urban areas (Tammeorg et al. 2021) and mine tailings (Hagner et al. 2021, Heiskanen et al. 2022), in addition to forest soils, could serve as examples of possible target areas where biochar could lead to greater benefits than in arable soils which have been frequently fertilized and limed. Indeed, the global meta-analyses have shown that yield increases are achieved for coarse-textured, nutrient-poor and acidic tropical soils, which in these respects resemble more non-arable soils in our focus region.

Water retention and hydraulic property impacts of biochar can be dependent also on the local climatic variables. For example, plant growth in arid regions would likely benefit of increased water retention, while sufficient drainage of the soils is also important in the wet boreal conditions. These demands for sufficient hydrological conditions for plant growth can be expected to vary interannually (for example dry versus wet years), which can partly explain the interannually varying crop yield impacts noticed also in this review. Long-term series analysis from experimental sites could help to understand in which hydrological conditions biochar could have the highest impact on crop production. The reviewed studies considering the ability of biochar to improve soil structural stability were inconsistent. Soil structural stability reflects the ability of soil to resist water erosion, and the use of several other soil amendments is motivated by their potential to serve as water-protection measures (Ekholm et al. 2024, Keskinen et al. 2025). Due to the contrasting findings, the literature reviewed does not enable a clear indication of whether biochar could serve in water protection, but apparently, other amendment types are more promising in this respect.

The scarcity of research on non-arable soils in northern conditions recalls for further systematic investigations on the biochar application on such soils in the future. Regarding agricultural soils, experimental results indicate that biochar has the potential to increase the long-term storage of carbon in the soil. In this respect, the absence of clear negative effects, e.g., on yield levels, is encouraging. However, if biochar is intended to be used to add recalcitrant carbon to soil, this requires economic subsidy mechanisms due to the absence of an enhancement in crop growth. It is also noteworthy that in field experiments, a considerable share of biochar was lost from the topsoil after a few years. This loss was linked to decomposition, leaching, and vertical and horizontal migration of the carbon added as biochar. While horizontal biochar transfer due to tillage can be an artefact of small plot size, transport of biochar out of the application area can reduce its impacts. The fate of this lost carbon in boreal conditions would be an interesting topic for future research.

Our literature review highlighted the scarcity of long-term investigations into the effects of ageing on biochar properties in boreal conditions, as well as the limited understanding of the impacts of biochar ageing on soil functioning. The two studies directly considering the ageing effects were conducted in forest soil environments, which differ from agricultural soil due to their management history and practices, i.e., frequent tillage, fertilization, and liming performed at arable fields, as well as soil type and properties. The obvious reason for the lack of biochar ageing studies in agricultural soils is that the research on this topic is fairly new in the target area, the earliest field experiments being established in 2009 by Karhu et al. (2011) and in 2010 and 2011 by Tammeorg et al. (2014a, 2014b). Some of the biochar field experiments have been revisited a few times after their establishment and there would be a need to continue their monitoring as the biochar application pursues long-term impacts, especially those related to storing recalcitrant carbon in soil. In addition to field monitoring, the changes in biochar properties caused by ageing in boreal soils and environment should be investigated, which would also help to decipher the results obtained in short-term laboratory incubations and the related soil structural and other laboratory analyses. Since there are several field experiments set up a decade ago, they would serve as excellent study sites for research focusing on biochar ageing in boreal arable soils and to study the impacts of biochar ageing on plant growth and soil physicochemical properties.

The positive impacts of biochar as a soil amendment on boreal soils appear rather limited. Nevertheless, this region has a lot of available biomasses that would be suitable for biochar production including mostly wood-based biomasses. A recent economic analysis, which assumed that biochar increases crop yields, concluded that in Finnish conditions farmers' incomes from increased yield, fertilizer savings and carbon subsidies are too small at the current biochar prices (Jokube et al. 2025). These aspects support the idea of finding applications where biochar could result in additional benefits to mere carbon storage in soil. It is important to notice that the Nordic biochar markets are still in the nascent stage (Salo et al. 2024) similarly to the carbon markets. Finally, we point out that while this review was limited to biochar impact on soil, there are other potential application areas, such as biochar cascade use approach in the agricultural context or valorization of biochar to be used in technical applications, worth studying**.**

Acknowledgements

The work was funded by Natural Resources Institute Finland (Luke).

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