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Effects of Biochar and Nitrogen-Enriched Biochar on Tree Growth in Scots Pine Stands

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ABSTRACT

Biochar, a carbon-rich product of pyrolysis, is increasingly considered for soil amendment and climate change mitigation due to its potential to enhance soil properties and sequester carbon. However, its effects on tree growth in forest ecosystems remain uncertain. This study investigated the impact of biochar and nitrogen-enriched biochar on the growth of two middle-aged (approximately 60-year-old) Scots pine stands in southeastern Norway. Both stands were characterized by medium site indices and podzolic soils. In replicated field experiments, we applied four treatments consisting of an unfertilized control, and addition of biochar (2.5 t ha^{-1}), nitrogen fertilizer (150 kg N ha^{-1}), or biochar loaded with nitrogen (2.5 t biochar +150 kg N ha^{-1}). The biochar was produced by pyrolysis of Norway spruce wood chips at 600°C. After 5 years, only treatments containing added nitrogen (either as mineral fertilizer or as nutrient-enriched biochar) significantly increased basal area and volume growth compared to control. No significant difference in timing or magnitude of effects was observed between the nitrogen and biochar + nitrogen treatments, except better annual growth in the combined treatment the third year after fertilization, indicating rapid nitrogen release and uptake regardless of carrier. Pure biochar did not stimulate tree growth. While biochar did not negatively affect growth, its direct role as a growth stimulant was not supported under these conditions, at least in the short-term with the dose of 2.5 t ha^{-1}. Further research is needed across different forest ages, site types, and application rates to fully understand biochar's potential in forestry.

1 | Introduction

Biochar is a carbon-rich solid residual material produced by pyrolysis, a process where organic material is heated under restricted access to oxygen (Lehmann and Joseph 2015). Biochar can be used for soil amendment or environmental management in a broader sense. Furthermore, adding biochar to soil is a potential tool for increased carbon storage and thus climate change mitigation (Fuss et al. 2018; Lehmann et al. 2021), as biochar is enriched in carbon and recalcitrant to decomposition (Gurwick et al. 2013; Wang et al. 2016) but also due to possibilities for carbon capture and storage (CCS) during production (Lehmann et al. 2021; Werner et al. 2018), reduced long-term mineralization of soil organic carbon (SOC) (Maestrini et al. 2015; Zhao et al. 2019), and increased plant growth (Joseph et al. 2021; Liu et al. 2013). The effect on plant growth is attributed to several factors. Biochar can increase microbial activity and enhance water holding capacity, soil porosity, cation exchange capacity, and pH (Biederman and Harpole 2013; Joseph et al. 2021; Lehmann and Joseph 2015; Palviainen et al. 2018; Robertson et al. 2012), thus working as a soil conditioner. Biochar properties vary substantially with feedstock and pyrolysis conditions (Ippolito et al. 2020; Liu et al. 2013).

A large number of studies on the effect of biochar as a soil amendment in agriculture have accumulated in the last two decades (Joseph et al. 2021). It has been shown that biochar can increase crop yields in agricultural soils, with the best effect on low-nutrient acidic soils and in sandy, dry soils (Biederman and Harpole 2013; Joseph et al. 2021). Research from Norway and the Nordic countries generally shows a modest positive effect on agricultural soil quality and non-significant effects on plant yield when untreated biochar was added to arable land (O'Toole et al. 2022).

Biochar amendment may also increase forest growth. A meta-analysis consisting of 17 studies indicated a potential for large tree growth responses after biochar additions, with a mean 41% increase in biomass (Thomas and Gale 2015). However, as most of the primary studies included were short-time pot experiments with tree seedlings, far-reaching conclusions cannot be drawn from this analysis. In recent years, more field studies have been established, and results are starting to emerge, even though studies in older forests are still lacking. Palviainen et al. (2020) found that biochar amendment (5 and 10 t ha^{-1}) on the soil surface increased tree growth in young Scots pine stands in Finland. Grau-Andres et al. (2021) added biochar (10 t ha^{-1}) either on the surface or mixed in soil before planting and found an increase in growth of Scots pine seedlings after nine years, resulting in an increase in C stored in biomass. Seedling survival also increased, but only when biochar was added to the soil surface. However, some field studies have also found negligible effects on forest tree growth. Sarauer et al. (2019) did not find any effect on tree growth after adding 2.5 or 25 Mg ha^{-1} biochar on the forest soil surface in North-Western US. Neither did Slesak and Windmuller-Campione (2024) find any significant effects on diameter or foliage mass of jack pine (*Pinus banksiana* Lamb.) seedlings the first four years after addition of biochar to the planting hole.

In northern forests on mineral soils, nitrogen (N) is usually the element that limits tree growth (Hedwall et al. 2014). The amount of N in biochar will vary with feedstock and pyrolysis temperature, but is usually low (Ippolito et al. 2020) and not readily available for plants (Lehmann and Joseph 2015). Even though biochar can contribute to increased N mineralization in forest soils through increased microbial growth, increased soil pH and decline in inhibitory phenolic compounds (Case et al. 2015; DeLuca et al. 2006; Gundale et al. 2016), plant growth is expected to increase more if high N content biochars, or biochar combined with a nitrogen source, is applied (Clough et al. 2013). Studies of the combined effects of biochar and mineral N fertilizers are lacking for boreal forests. Field experiments with ordinary mineral fertilization are, on the other hand, plentiful. In the Nordic countries, forest fertilization is usually practiced by adding ca. 150 kg N ha^{-1} once or twice during a rotation period, mainly in forests approaching maturity. The nitrogen fertilizer is commonly based on ammonium nitrate, and the expected increase in stem growth is around 10–20 m^3 ha^{-1}, with the effect ending within 6–10 years (Hedwall et al. 2014; Ingerslev et al. 2001; Nilsen 2001). Downsides of forest fertilization can be increased leaching of nutrients to water systems (Binkley et al. 1999; Lundin and Nilsson 2021) and adverse effects on vegetation and mycorrhiza (Hedwall et al. 2018; Strengbom and Nordin 2008; Sullivan and Sullivan 2018) and thus there are regulations on the use of mineral fertilizers, for example, in Norwegian forestry (Anon 2022; Ask et al. 2021). Biochar, with its large surface area and content of functional groups and variable surface charges (Lehmann and Joseph 2015; Li, Hu, et al. 2018; Palviainen et al. 2025), can potentially act as a nutrient carrier in forest fertilization, with slower release of nutrients and reduced leaching as conceivable benefits (Brtnicky et al. 2023; Clough et al. 2013; Kohira et al. 2025; Wang et al. 2022). Development of nutrient-enriched biochars is an active research area and it has been shown that such designed biochar fertilizers applied at similar NPK rates as mineral fertilizers has substantially increased N use efficiency of crops (Bai et al. 2022; Nguyen et al. 2017; Ye et al. 2020; Zheng et al. 2017).

Today, only a few field studies have explored the effect of biochar in forests beyond the sapling stage, and experiments combining biochar with mineral fertilizers are virtually lacking for boreal forests. Consequently, further knowledge is required on the long-term impacts of biochar and N-enriched biochar on stand-level growth and yield, highlighting the need for field experiments encompassing a range of biochars, soil types, forest ecosystems, and climatic conditions (Page-Dumroese et al. 2017; Palviainen et al. 2020).

The aim of our study was to examine the effect of adding biochar and nitrogen enriched biochar on the growth of middle-aged Scots pine stands in Norway. Based on previously reported findings, our hypotheses were: (1) adding pure biochar will increase forest growth, (2) adding nitrogen enriched biochar will increase forest growth more than adding a similar amount N through mineral fertilizer, and (3) the positive growth effect of adding nitrogen enriched biochar will start slower and last longer than with mineral fertilizer only.

2 | Materials and Methods

2.1 | Study Sites and Experimental Design

The field experiment was performed in two Scots pine stands on medium site indices in SE Norway (Table 1). The Nesteby site is situated in Kongsvinger municipality on relatively flat, dry, and sandy podzolic soil, originally formed by flood deposition from glacier lake drainage (Norwegian Geological Survey 2024, www.ngu.no). The vegetation is dominated by lichens (*Cladonia* ssp.) and mosses (e.g., *Pleurozium schreberi, Dicranum* ssp.).

The Kjennsmo site is in Nes municipality on podzolic, gently sloping thin marine deposits. Dominating vegetation species are bilberry, lingonberry and mosses (e.g., *Pleurozium schreberi, Hylocomium splendens* and *Dicranum* ssp.).

During the 5-year study period, mean annual temperature and precipitation at the sites were close to the long-term averages shown in Table 1 in 2021, 2023 and 2024, according to the Norwegian Meteorological Institute (www.met.no/en). In contrast, 2020 was warmer and wetter, with mean annual temperatures 2.6°C and 2.2°C above average at Nesteby and Kjennsmo, respectively, and precipitation about 30% higher than the values shown in Table 1. By comparison, 2022 was relatively warm and dry, with mean annual temperatures about 1°C above average and precipitation about 15% below the values shown in Table 1.

In each site, four treatments were applied in a block design: an unfertilized control (Control), 2.5 t ha^{-1} biochar (BC), 150 kg ha^{-1} of N given as ammonium nitrate (N) and 2.5 t ha^{-1} biochar loaded with 150 kg ha^{-1} of N (BC + *N*). There were three replicates (blocks) of the treatments on each site, and treatments were randomly assigned within each block. Treatment plot size was 25 × 25 m, including a 5 m buffer zone (Figure 1). All sampling was carried out in the inner 15 × 15 m area, and there were between 6 and 19 trees in each of these inner plots. Before treatment, diameter at breast height (DBH) and height of all trees were measured with a pi tape and a Vertex III (Haglöf, Sweden), respectively. Stem volume per plot was calculated using the volume functions of Brantseg (1967). Stand characteristics before treatment are given in Table 1.

TABLE 1 | Site and stand characteristics of the experimental sites at time of establishment.

Site	Nesteby	Kjennsmo
Latitude and longitude	60°12′ N, 12°06′ E	60°01′ N, 11°27′ E
Altitude (m a.s.l.)	185	190
Mean annual temp (°C)[a]	5.3	5.3
Mean annual precipitation (mm)[a]	704	729
Site index (H40)[b]	F17	F14
Site quality (m^3 ha^{-1} year^{-1})	7.0	5.0
Stand age (ca.)	57	58
Standing volume (m^3 ha^{-1})	214	214
Basal area (m^2 ha^{-1})	22.0	23.3
Stems ha^{-1}	559	593
Mean tree height (m)	20.5	19.4

[a]Mean values 1991–2020. The Norwegian Meteorological Institute.
[b]Tveite (1977).

The ammonium nitrate fertilizer was Opti-KAS Skog (Yara), containing 27% N (13.5% as NO^{3-} and 13.5% as NH^{4+}), 5% Ca, 2.4% Mg and 0.2% B. The biochar was provided by Standard Bio, Norway, produced by pyrolysis from Norway spruce (*Picea abies*) wood chips (size 5–10 mm) at 600°C. The elemental composition of the biochar was measured by Eurofins lab according to DIN 51732, and the biochar contained 91.4% C and 0.17% N. The BC + *N* was made by loading the biochar with fertilizer. This was done by first mixing water and Opti-KAS Skog, followed by adding also biochar in a large mixer under constant stirring until the fertilizer dissolution was taken up by the biochar. The loaded biochar contained 5.8% total N (Eurofins lab). Fertilizer, biochar and loaded biochar were spread manually on top of the organic layer in June 2020.

Measurements of DBH and tree height were conducted again at the end of August 2024, five growing seasons after treatment. At the same time, increment cores spanning the last 10 years were taken at breast height. Cores were taken from different compass angles, depending on the direction from which the tree was approached. The width of the annual rings was measured with a resolution of 0.01 mm using TSAP-Win (Rinntech, Germany).

2.2 | Statistical Analysis

The effect of fertilization treatments on annual ring width was analysed using a linear mixed-effects model with treatment as a fixed factor. Average ring width in the 5 years prior to treatment (2015–2019) was included as a covariate to adjust for initial growth differences between trees. Site and block nested within site were included as random effects to account for the

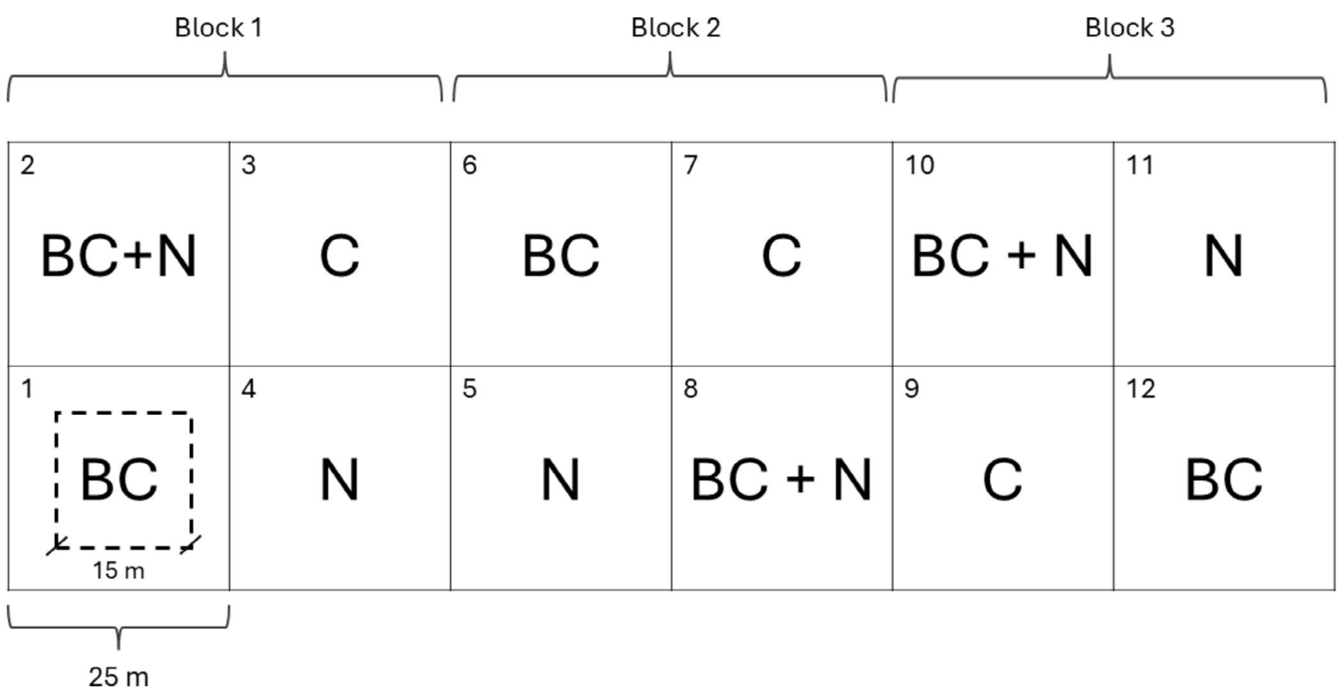

FIGURE 1 | Experimental design shown for one of the sites, with four treatments randomly assigned within each of the three blocks. BC = biochar, *N* = ammonium nitrate, BC + *N* = biochar + ammonium nitrate, C = unfertilized control. All measurements took place in the 15 × 15 m inner plots.

hierarchical structure of the experiment. Individual trees were treated as observational units. The model had the form

$$y_{ijkl} = \mu + \tau_k + \beta x_{ijkl} + s_i + b_{j(i)} + \varepsilon_{ijkl} \quad (1)$$

where y_{ijkl} is the annual ring width in 2024 for tree l receiving treatment k, located in block j within site i; μ is the overall mean; τ_k is the fixed effect of treatment; x_{ijkl} is the covariate (average ring width prior to treatment) with associated slope β; $s_i \sim \mathcal{N}\left(0, \sigma_f^2\right)$ is the random effect of site; $b_{j(i)} \sim \mathcal{N}\left(0, \sigma_b^2\right)$ is the random effect of block nested within site; and $\varepsilon_{ijkl} \sim \mathcal{N}\left(0, \sigma^2\right)$ is the residual error. Degrees of freedom were approximated using the Kenward–Roger method.

The effects of the treatments on the mean annual volume increment as well as standing volume and basal area 5 years after treatment were analyzed with linear mixed-effects models with the same random-effects structure. Treatment was included as a fixed factor, and pre-treatment stand characteristics were included as covariates. The model had the form

$$y_{ijk} = \mu + \tau_k + \beta x_{ijk} + s_i + b_{j(i)} + \varepsilon_{ijk} \quad (2)$$

where y_{ijk} is the response variable for treatment k in block j at site i; μ is the overall mean; τ_k is the fixed effect of treatment; x_{ijk} is a continuous covariate describing pre-treatment stand conditions; $s_i \sim \mathcal{N}\left(0, \sigma_f^2\right)$ is the random effect of site; $b_{j(i)} \sim \mathcal{N}\left(0, \sigma_b^2\right)$ is the random effect of block nested within site; and $\varepsilon_{ijk} \sim \mathcal{N}\left(0, \sigma^2\right)$ is the residual error.

For analyses of annual volume increment and standing volume 5 years after treatment, the covariate x_{ijk} corresponded to standing volume in 2019, whereas basal area in 2019 was used as the covariate when modelling basal area 5 years after treatment. All analyses were conducted using the GLIMMIX procedure in SAS (SAS Institute Inc., Cary, NC, USA). Pairwise comparisons among treatments were performed using Tukey–Kramer adjustments. Assumptions of normality and homogeneity of variance were evaluated graphically. The value 0.05 was used as significance level for all analyses.

3 | Results

3.1 | Volume and Basal Area

Before treatment, there were no significant differences in standing volume or basal area between plots designated to the different treatments. Five years after treatment, however, both average annual volume increment, standing volume and basal area were larger for the N and BC + *N* treatments than for the BC treatment and Control. There were no differences between sites. Table 2 shows that treatments had a strong significant effect on both the basal area and volume development. The annual volume increment according to the model is shown in Figure 2. The modelled standing volumes 5 years after treatment were 254, 252, 264 and 265 $m^3\ ha^{-1}$ for Control, BC, N and BC + *N*, respectively, while the corresponding basal areas were 25.5, 25.5, 26.3 and 26.5.

3.2 | Increment Cores

The first autumn after treatment no differences in the growth of annual rings were found. However, from the second year on, trees in treatments N and BC + *N* grew better than in Control and BC (Figure 3). The effect was largest in the third year, when increment in the N and BC + *N* treatment was 137% and 157%, respectively, compared to Control. There was a significant difference between N and BC + *N* only in 2022, when trees in the BC + *N* treatment grew better. After the fifth growing season the annual ring growth in the two treatments containing nitrogen was still higher than in Control and BC plots. However, the annual growth was now clearly decreasing.

The annual growth of the trees in the BC treatment was almost identical to the Control treatment throughout the period, with both showing a declining trend.

4 | Discussion

We tested the effect of adding biochar, nitrogen, or a combination of the two on the growth of two middle-aged pine stands. Results after 5 years showed that the treatments containing nitrogen, either applied alone or in combination with biochar, resulted in better growth than in the unfertilized control, while the treatment with pure biochar did not have an effect. The declining growth trend in the control and biochar plots throughout the study period is difficult to attribute to weather conditions and likely reflects that growth is on its way down in these middle-aged Scots pine stands.

Our first hypothesis, that addition of biochar alone would increase growth, was thus not confirmed. The absence of a positive effect of pure biochar on tree growth observed in our study may mainly be attributed to N limitation, as nitrogen is the element usually restricting biomass production in the Nordic forests (Hedwall et al. 2014; Tamm et al. 1999). This was also demonstrated by the rapid growth effect of adding N in our two other treatments. Even though biochar can increase N mineralization

TABLE 2 | *F* statistic and *p* values of the measured effects of biochar/fertilizer treatment 5 years after treatment. Basal area (BA) in 2019 was used as a covariate for the basal area analysis, while standing volume (VOL) in 2019 was used for the volume analyses.

	Basal area		Volume increment		Standing volume	
	F	***p***	***F***	***p***	***F***	***p***
Treatment	17.26	< 0.0001	14.84	< 0.0001	14.84	< 0.0001
BA or VOL 2019	5728.80	< 0.0001	82.02	< 0.0001	3204.31	< 0.0001

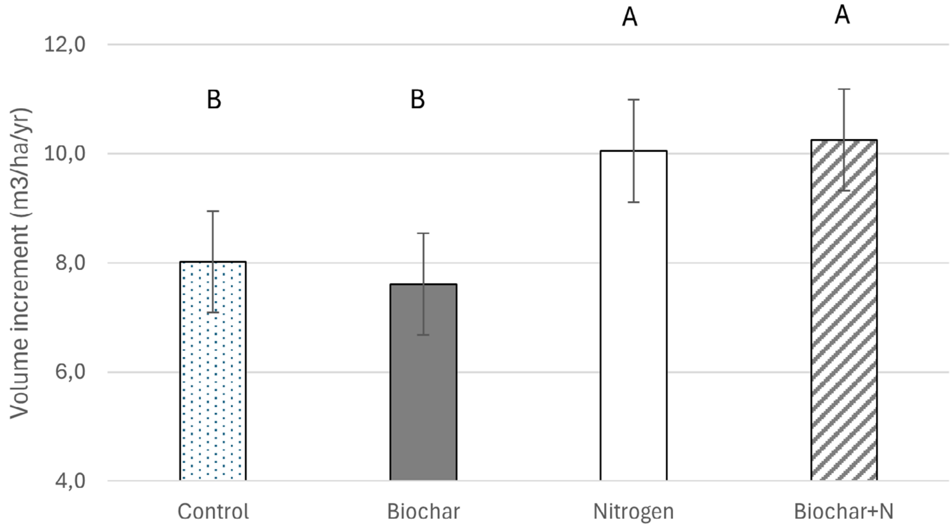

FIGURE 2 | Average yearly volume increment in the first 5-year period for the different treatments, ±SE.

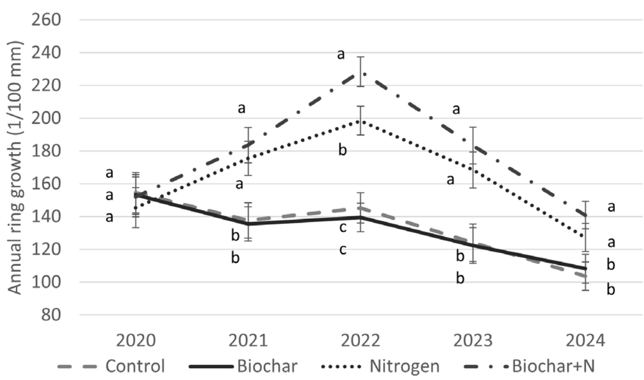

FIGURE 3 | Modelled annual ring growth (1/100 mm) for the different treatments in the 5-year study period. ±SE.

in forest soils (DeLuca et al. 2006; Gundale et al. 2016), the effect of our rather modest dose of 2.5 t ha^{-1} may be too small to modify forest growth.

Furthermore, as we added the biochar on top of the organic layer, it may not yet have had a significant impact on the chemical and physical properties of the mineral soil (Sarauer et al. 2019). After one season there were hardly any visible biochar fragments on top of the vegetation in our study, but when the vegetation layer was pulled aside, fragments were easily spotted and abundant in the humus layer. This was the case also at the end of the experimental period. Changes resulting from biochar application may develop gradually as the biochar moves downward through the soil profile through bioturbation and translocation. A rapid mix of biochar and soil can only be achieved if biochar is added during the regeneration stage and mixed, for example, using disc trenchers or excavators. Later in the stand's life, like at our sites, there is no other possibility than adding it to the surface to avoid soil disturbance and damage to roots (Hanssen et al. 2023; Palviainen et al. 2020).

The sites used in our study were on medium rich soils, according to the site indices. Agricultural trials have usually found the most pronounced effects of biochar on poor, acidic and dry soils (Biederman and Harpole 2013). Our sites were, for example, richer than those used by Palviainen et al. (2020), who found that biochar amendment of 10 t ha^{-1} in a young Scots pine forest increased diameter growth substantially, while 5 t ha^{-1} increased height growth during the first 3 years. The lower doses added in our experiment may also have contributed to the different result. In addition, our Scots pine forests were older. Higher tree age could result in slower responses to biochar amendment, as mentioned by Sarauer et al. (2019) who neither found any positive growth effect of adding pure biochar in 13–44 year old conifer dominated forests in western US. There are, however, very few reported field studies with biochar addition to older conifer forests.

Adding nutrient enriched biochar clearly increased both basal area and volume increment. Even though annual ring growth was higher for BC + *N* than for N in the third year after fertilization, we did not find any other significant differences in magnitude or timing of the effect compared to adding mineral fertilizer, contradicting our second and third hypotheses. The level of increase as well as the development over time for both these treatments were in line with other studies from the Nordic countries using mineral N fertilizers (Hedwall et al. 2014; Nilsen 2001). This indicates that N was released rather quickly from the biochar and utilized by the pine trees in a similar way as the N from the pure mineral fertilizer during the 5-year study period. As the effect of N-addition is still visible in the growth of the annual rings at the end of the period (Figure 3), we cannot completely rule out differences in growth in the coming years. Therefore, we are not yet able to draw a final conclusion regarding the validity of the third hypothesis.

An experiment utilizing ^{15}N isotope tracers that was performed in the Nesteby site, just outside our experimental plots, shed light on the fate of N when given either as conventional N fertilizer or as N-enriched biochar. Despite an improved retention of ^{15}N in the humus when N-enriched biochar was used, a substantial portion of the applied ^{15}N from both treatments was observed to move below the root zone relatively quickly (Weldon et al. 2025). Even though this experiment used another N source (but the same type of biochar), it confirmed that nitrogen leaching occurred in these sandy, well-drained podsolic soils also with biochar used as a carrier.

The properties and effects of nutrient-enriched biochar will depend on the form of nutrient source as well as biochar properties (Joseph et al. 2021; Kohira et al. 2025). For instance, co-application of biochar with organic fertilizers has been shown to be more effective in reducing NO_3^- -N leaching compared to mineral fertilizers (Kohira et al. 2025). Furthermore, methods such as impregnation, encapsulation, or granulation can be used to produce and improve slow-release biochar-based fertilizers (Wang et al. 2022).

Both pyrolysis temperature and feedstock affect the physiochemical properties of biochar and thereby the N retention (Li, Barreto, et al. 2018; Wang et al. 2022). Biochars produced at high temperatures have a larger specific surface area (SSA) (Ippolito et al. 2020) and have higher potential for mitigating N losses and improving N use efficiency (Kohira et al. 2025). However, the biochar used in our experiment was produced at a relatively high temperature (600°C) and from wood, a feedstock that generally also gives high SSA (Ippolito et al. 2020; Li et al. 2023), and should thus be well suited for N retention and improving soil conditions.

The fact that a positive effect on tree growth from biochar addition is uncertain may cause forest owners to hesitate to invest in the treatment. There are also barriers to the widespread use of biochar in forests due to high production costs and lack of available biomass (Fuss et al. 2018; Palviainen et al. 2025). However, our findings indicate that biochar does not adversely affect tree growth, and increased carbon storage in soil after biochar amendment remains a positive climate mitigation effect (Fuss et al. 2018; Lehmann et al. 2021). The development of carbon credit systems may improve the economics of this measure in the future (Hanssen et al. 2023; Pan et al. 2022).

Our field study is one of very few in older boreal forests. More studies in middle-aged and mature forests, on different site types, longer time scales and with different doses are needed to draw reliable conclusions about the effects of biochar addition on tree growth.

5 | Conclusions

In our two field experiments in medium rich, middle-aged Scots pine stands in SE Norway, 5-year growth did not increase after addition of 2.5 $t\,ha^{-1}$ biochar. Adding an N dose of 150 $kg\,N\,ha^{-1}$ and adding biochar loaded with the same N dose both increased basal area and volume growth. There was no difference in effect or timing of the two treatments containing N during the 5-year period. The findings indicate that under the given site conditions and application rate, biochar does not act as a direct growth stimulant. To draw reliable conclusions about the effects of biochar addition on tree growth, further research comprising a variety of field conditions, application doses and time scales is needed.

Author Contributions

Rasmus Astrup: conceptualization, funding acquisition, writing – review and editing. **Jogeir Stokland:** conceptualization, methodology, funding acquisition, project administration, writing – review and editing. **Kjersti Holt Hanssen:** conceptualization, methodology, data curation, investigation, validation, formal analysis, writing – original draft, project administration, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data presented in this study is available from the corresponding author upon reasonable request subject to a data-sharing agreement.

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