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Research article

How does forest fertilization influence tree productivity of boreal forests? An analysis of data from commercial forestry across Sweden

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ABSTRACT

Forest fertilization is a forest management practice that is often claimed to increase productivity in boreal forests. Although regarded as an efficient way to increase profitability, it is also costly, and associated with risks such as biodiversity loss and nitrogen leaching from the soil. To be both cost-efficient and sustainable, potential enhanced productivity due to fertilization should be balanced against the adverse environmental impact. One effective strategy is to limit fertilization to sites where it can most significantly increase tree productivity, while avoiding application in less suitable areas. However, the current understanding of the specific conditions under which forest fertilization optimally stimulates tree growth is limited. To clarify this, we analysed standing tree volume from 32,498 recently harvested fertilized and unfertilized stands from Sweden's largest forest owner. We applied generalized additive models to quantify the effect of fertilization on standing tree volume at harvest and how the fertilization effect depended on dominant tree species, stand characteristics (site index, stem density), climatic conditions (temperature sum), and management (thinning, stand age at harvest). We found that the effect of operational fertilization was highly context-dependent. In pine-dominated stands, fertilization failed to increase tree volumes in cold climates and low-productive stands. In spruce-dominated stands, fertilization did not result in increased tree volumes in low-productive and high-productive stands. For a more sustainable and cost-efficient application of this practice we suggest that the context dependency of the efficiency of fertilization is given more attention. Hence, we recommend to refrain from fertilizing pine-dominated stands situated on low-productive land or in regions with cold climates, such as those found in northern Sweden.

1. Introduction

Considering the significance of boreal forests in generating forestry incomes, storing carbon, and supporting biodiversity, their management holds substantial environmental and economic implications. Boreal forests are estimated to store one third of the global forest carbon stock (Bradshaw and Warkentin, 2015; Pan et al., 2011). Management can enhance the carbon stock in forests by increasing tree productivity, but it can also contribute to carbon storage in the form of long-lived forest products and reduce CO_2-emissions by providing raw material for substitutes of fossil carbon (Lundmark et al., 2014). Tree growth in boreal forests is nitrogen limited (Tamm, 1991), and experiments have demonstrated that tree biomass production and carbon sequestration may increase substantially following nitrogen additions (Bergh et al., 2014; Hyvönen et al., 2008; Jörgensen et al., 2021; Saarsalmi and Mälkönen, 2001). Anthropogenic nitrogen deposition has been estimated to induce additional sequestration of 11 (CI_{95}: 4–21) kg carbon per kg of deposited nitrogen in boreal forests (Schulte-Uebbing et al., 2022). Nitrogen enrichment in boreal forests also occurs through forest fertilization, which is a common practice to improve productivity in Fennoscandia (Lindkvist et al., 2011; Saarsalmi and Mälkönen, 2001). While nitrogen addition can increase productivity and carbon stocks in boreal forests, it is also costly (Simonsen et al., 2010), can increase nitrogen leaching from the soil (Berdén et al., 1997; Lundin and Nilsson, 2021; Nohrstedt, 2001), and has negative effects on forest biodiversity (Hasselquist and Högberg, 2014; Hedwall et al., 2019; Maaroufi et al.,

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2019; Rodríguez et al., 2021; Strengbom and Nordin, 2008; Strengbom et al., 2001). Therefore, to ensure sustainable profitability and to minimize adverse environmental effects, fertilization should only be applied where the positive effects are substantial enough to justify the negative consequences.

Despite the long-recognized potential to increase productivity through forest fertilization (Swan, 1965), its practical application in forestry has never been nearly as widespread as it is in agricultural systems (Smethurst, 2010). Historically, forest fertilization has been predominantly practiced in Fennoscandian countries (Nohrstedt, 2001; Saarsalmi and Mälkönen, 2001). However, interest in forest fertilization may increase due to its potential to enhance the carbon sink of forests, thereby mitigating global warming (Jörgensen et al., 2021). In Sweden, forest fertilization was applied extensively from the late 1960s until the late 1980s. Since the early 2000s, interest in forest fertilization has increased again, and fertilization has been promoted as a way to rapidly increase forest productivity (Skogforsk, 2008), but also as a tool to mitigate global warming through increased carbon sequestration (Mayer et al., 2020; Mäkipää et al., 2023). However, since the effects of nitrogen addition may be context-dependent (Hyvönen et al., 2008; Jörgensen et al., 2021), its effectivity likely varies across sites. According to experiments, the effect on tree growth may depend on tree species, latitude, site fertility, as well as management practices (fertilizer dose, fertilization intervals, thinning regime etc.) (Bergh et al., 2014; Blaško et al., 2022; Eriksson, 2006; Hyvönen et al., 2008; Jörgensen et al., 2021; Kellomäki, 2022; Thurm and Pretzsch, 2021). The two main tree species of interest in Fennoscandian forestry; Norway spruce (*Picea abies* L. Karst., hereafter 'spruce') and Scots pine (*Pinus sylvestris* L., hereafter 'pine'), have different growth and resource allocation patterns (Blaško et al., 2020), resulting in different responses to fertilization. Spruce grows better than pine in more fertile sites and responds more strongly to fertilization in less fertile stands (Nilsson et al., 2012; Saarsalmi and Mälkönen, 2001). Responses to fertilization are, however, complex, as the growth response of spruce appears to be slower, but more long-lasting than that of pine (Pettersson, 1994a). Spruce retains its needles longer than pine, which may cause a slower but longer-lasting responsiveness to increased nutrient availability. Furthermore, fertilization of middle-aged stands appears to be most effective in economic terms, as fertilization of young trees increases branch diameter rather than basal area, thereby decreasing wood quality (Saarsalmi and Mälkönen, 2001). Also the belowground immobilisation of added nitrogen likely depends on tree species and their carbon allocation patterns (Högberg et al., 2021; Sterkenburg et al., 2015).

Southernmost Sweden has a history of elevated anthropogenic nitrogen deposition, with current deposition in the range of 8–16 kg N ha^{-1} $year^{-1}$ (Karlsson et al., 2022). Thus, as a safety measure to minimize the leaching risks associated with nitrogen saturation (Akselsson et al., 2010), fertilization is restricted to the northern two thirds of Sweden (above 59° N). Currently, fertilization is restricted to 300 kg N ha^{-1} and 450 kg N ha^{-1}, in central and northern Sweden, respectively, with a maximum of 200 kg N ha^{-1} per round and at least 8 years between rounds of fertilization (Skogsstyrelsen, 2011). Furthermore, some habitat types are exempted from fertilization, including sites with a very high fertility (site index >30) or very low fertility (site index <16 or soils covered by lichens), sites with shallow soils, peat soils (>30 cm of peat depth) or soils with high water permeability, sites on slopes and sites that are particularly valuable for biodiversity conservation. These recommendations are based on nutrient addition experiments (Pettersson, 1994b, 1994c). While such experiments have the advantage of controlled and comparable conditions, they have the disadvantages of limited replication and poor representation of site variation, which implies that they are less suitable for addressing differences in fertilization response in relation to variation in stand characteristics. In addition, most of these experiments have only examined short-term growth responses, while the final harvestable tree volume, which is most relevant from an economic perspective, has received limited attention.

To develop a new forest fertilization regime that encompasses a broad range of aspects, such as profitability, carbon sequestration, and negative impacts on the environment, we need a better understanding of the context dependency of fertilization effects. Thus, this study aims to assess how the effect of operational fertilization on the standing tree volume at harvest is modified by dominant tree species (pine or spruce) and site conditions (stem density, fertility, and climate). In order to achieve this, we used a dataset from Sweden's largest forest owner, covering the entire latitudinal range of the boreal biome.

2. Material and methods

The data was obtained from Sveaskog AB, which owns 3.9 million ha or ca. 14% of all forest land in Sweden. Sveaskog's stand database contains detailed information on stand characteristics, such as stand area, tree species composition, site index, stem density, soil type, soil moisture class, mean age of the trees, and information on thinning and fertilization operations. The site index gives an estimate of the potential site productivity and is defined as the expected average height of the dominant tree species at a chosen reference age (Skovsgaard and Vanclay, 2008), normally 100 year for pine and spruce. For example, a site index of 28 predicts that the average height of the largest 100 trees per hectare in the stand will be 28 m at the age of 100. For logged stands, the database also contains information on standing and extracted timber volumes per tree species at the time of final harvest. The volumes are estimated in field inventories by trained personnel during the planning of the final harvest, based on measurements of basal area (estimated by relascope) and height per tree species at sites distributed within the stand. The number of sites varies depending on the heterogeneity of the stand. Measured data is converted into volumes based on allometric functions developed by Marklund (1988). The accuracy of estimates is regularly checked by matching them to more detailed field inventories where diameter and height of individual trees are measured and used for volume estimates, and occasionally by matching volume estimates to data on actual harvest volumes from harvester machines. These volume estimates are central for the company's operational planning, both in terms of forest- and business management, and during quality checks, estimates are not allowed to deviate by more than c. 10% for an individual planner.

We selected stands on moraine soils and with a minimum area of 2 ha and a minimum age of 50 years. As no fertilized stands contained trees older than 175 years, we omitted 36 unfertilized stands with older trees from the analyses. Prior to further analyses, we also omitted 208 stands that most likely contained data entry errors, such as stands with unrealistic volumes of extracted wood (<0 or >1500 m^3 ha^{-1}). In total, we used data from 32,498 forest stands across Sweden, which were split up into two datasets according to the dominant tree species: 21,846 pine-dominated stands (>50 % basal area of pine) and 10,652 spruce-dominated stands (>50 % basal area of spruce). This split was based on known differences in response to fertilization between spruce and pine (Nilsson et al., 2012; Pettersson, 1994a; Saarsalmi and Mälkönen, 2001) and on initial analyses that confirmed the different responses to fertilization. Separate models per dominant tree species facilitated more straight-forward interpretation of the statistical models (i.e., less high-order interactions). Since not all stands were managed in the same way in terms of thinning operations, and since thinning can influence the harvestable volume and potentially interact with the fertilization effect (Bergh et al., 2014; Jörgensen et al., 2021), thinning was included as a factor in our analysis. Almost half of the stands were thinned before the final harvest, and around a third were fertilized at least once (Table 1). The common fertilization practice is to apply 150 kg N ha^{-1} per fertilization event in the form of ammonium nitrate. The most commonly used fertilizer is Skog-CAN (Yara ©), which is ammonium nitrate with added dolomite ($CaMg(CO_3)_2$), to reduce the risk of acidification, and 0.2% boron (B). Previously, both urea and pure ammonium

Table 1
Number of stands included in the analyses. Two separate datasets were used: one with pine-dominated stands (>50% basal area of pine), and one with spruce-dominated stands (>50% basal area of spruce). Around half of the stands were thinned before harvesting and around a third were fertilized at least once.

		Fertilized	Unfertilized	Total
Pine-dominated	Thinned	5532	5910	**11,442**
	Unthinned	2439	7965	**10,404**
	Total	**7971**	**13,875**	**21,846**
Spruce-dominated	Thinned	1837	4050	**5887**
	Unthinned	887	3878	**4765**
	Total	**2724**	**7928**	**10,652**

nitrate were used (Nohrstedt, 2001), but urea was abandoned already in the early 1970s, and pure ammonium nitrate was replaced by Skog-CAN in the 1980s (Kardell and Lindkvist, 2010).

To quantify the effects of fertilization on standing tree volume at harvest, we fitted tree species-specific models that included fertilization (fertilized/unfertilized) as the key predictor. Environmental variables and thinning (thinned/unthinned) were added and their two-way interactions with fertilization were included to estimate how thinning and the environment modified the effects of fertilization. These environmental variables were site index, age at harvest, stem density, and temperature sum of all days above 5 °C over 1 year (hereafter 'temperature sum'). Temperature sum was used, as it is mechanistically linked to growth and frequently used in boreal tree growth models (e.g. Matala et al. (2006) and integrates variation in latitude and altitude (Fig. S1), thereby reducing the number of variables included in the model. To account for climatic effects on site index, the residuals of a linear model of site index as a function of temperature sum were used as a 'temperature-detrended site index' (Fig. S2). In our modelling, we assume that selection bias, i.e., that fertilization has not been randomly assigned to stands, is mostly accounted for by including the environmental variables that are known to affect tree growth. Our data indicated that the distribution of fertilized stands along our environmental variables were not severely skewed compared to non-fertilized (Fig. S3).

We used generalized additive models for model fitting. By using a smooth function of covariates instead of a linear predictor, generalized additive models allow for more flexible specification of the dependence of response variables on predictors than in generalized linear models (Wood, 2017). Thin plate regression splines were used as the smoothing basis function, and smoothing parameters were estimated using REML. The choice of the basis dimension for each of the smooths was evaluated by increasing the basis dimension and subsequently checking the fit. In order to minimize the effect of gaps in data points on the smooth and avoid overfitting, the basis dimension was limited to five. All data processing and analyses were carried out in R version 4.1.2 (R core team, 2021). Model fitting was executed using the R package *mgcv* (Wood, 2017), estimated marginal means and model estimates were extracted using the R packages *emmeans* (Searle et al., 1980) and *tidymv* (Coretta, 2022), and results were visualized using the R packages *ggplot2* (Wickham, 2016), *tidymv* (Coretta, 2022) and *ggpubr* (Kassambara, 2020). The input data are property of Sveaskog and cannot be released publicly but can be accessed by contacting the authors.

3. Results

Overall, fertilized stands had a higher standing tree volume than unfertilized stands. However, for spruce-dominated stands, the difference was only detected for unthinned stands (Fig. 1). For pine-dominated stands fertilization had a significant effect in both thinned and unthinned stands. The difference between fertilized and unfertilized stands was on average (i.e. other predictors held at average values for each data set) 16.6 and 19.5 m^3 ha^{-1} in thinned and unthinned pine-

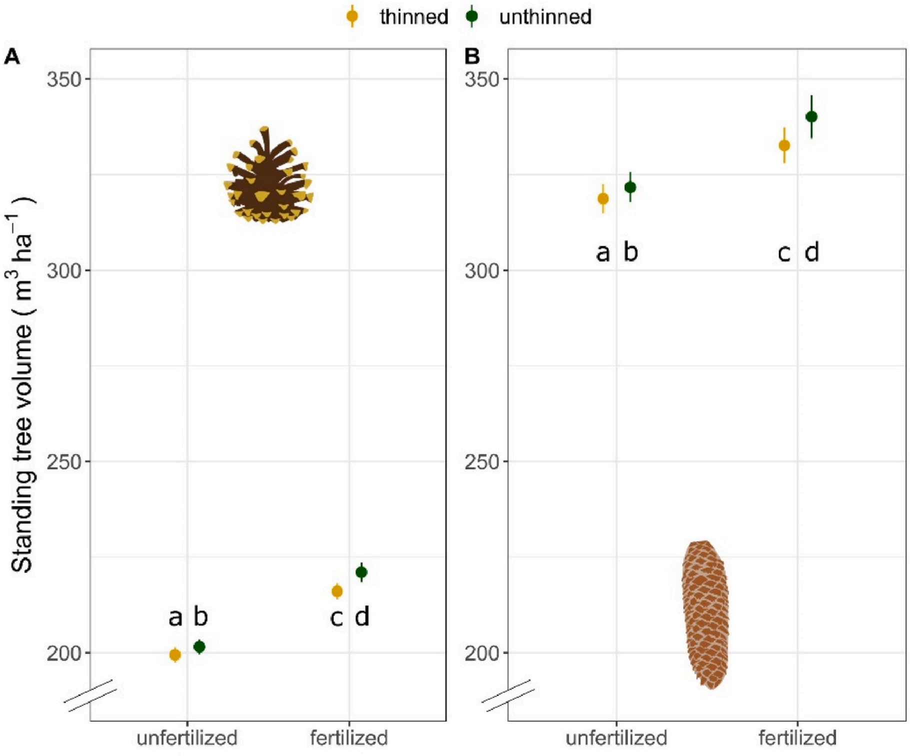

Fig. 1. Estimated marginal means (EMMs) and 95% confidence intervals of standing tree volume at harvest in (A) pine-dominated and (B) spruce-dominated stands, obtained from their respective model. The covariates temperature-detrended site index, stand age at harvest, stem density and temperature sum are set at the average, which differs for pine- and spruce-dominated stands (Table S1). Note that because the effects are evaluated at the same stem density, thinning effects are partly obscured. For a comparison of pine- and spruce dominated stands under the same conditions, see Fig. S2. Letters indicate significantly different EMMs.

dominated stands, respectively, and 13.9 and 18.4 m^3 ha^{-1} in thinned and unthinned spruce-dominated stands, respectively. This corresponds to growth increases of 8.4 %, 9.6 %, 4.4 %, and 5.7 % in thinned pine-dominated, unthinned pine-dominated, thinned spruce-dominated, and unthinned spruce-dominated stands, respectively. Spruce-dominated stands had much higher standing tree volumes (on average 319–340 m^3 ha^{-1}, depending on fertilization and thinning, Fig. 1) than pine-dominated stands (on average 199–216 m^3 ha^{-1}, Fig. 1), but spruce-dominated stands were also less frequent in the north and had a higher average site index (Table S1, Fig. S1). However, productivity was higher in spruce-dominated stands even when differences in site conditions were taken into account (Fig. S4, Table S2).

The model for pine-dominated stands explained 71.9 % of the variation, and all of the main effects were highly significant (Table 2). Fertilization interacted significantly with thinning, temperature-detrended site index, stand age and temperature sum (Table 2, Figs. 2 and 3). Standing tree volume increased with temperature sum, but levelled off around 1400 °C (Fig. 2A), which, depending on the altitude (see Fig. S2), corresponds to a latitude of 56–60 °N. There was no significant difference between fertilized and unfertilized stands below temperature sum 800 °C, which corresponds to stands situated at the highest altitudes at latitudes 61–66 °N and stands at all altitudes above latitude 66 °N (Fig. S3). Moreover, we detected no difference between fertilized and unfertilized stands in the least fertile stands (Fig. 2C), which had temperature-detrended site indices below −3 (corresponding to site index of 14 in the north, and to 22 in the south, Fig. S4). In total 4647 stands, or 21.3 % of the pine-dominated stands in our data set, had a temperature sum below 800 °C or a detrended site index below −3, meaning they were not suitable for fertilization. In total 1355 stands identified as unsuited for fertilization were, nevertheless, fertilized (accounting for 17.0 % of the fertilized pine-dominated stands). Fertilization interacted significantly with stand age, with an increasing difference between fertilized and unfertilized stands up to ca. 100 years (Fig. 3A). The apparent lower standing volumes in the youngest (<65 years) fertilized stands compared to unfertilized stands is most likely due to the lower proportion of fertilized stands at the highest temperature sums (Fig. S5A), where productivity is also higher. In stands older than 65 years at harvest, this bias was not apparent (Fig. S5B), supporting the validity of the identified interaction.

Table 2

Outcome of the generalized additive model on the pine-dominated stands (R^2_{adj} = 0.719, n = 21,846). k: number of basis functions, EDF: estimated degrees of freedom, temperature sum 5: temperature sum of all days above 5 °C, accumulated over 1 year.

Parametric terms

Variable	Estimate	Standard Error	F	p-value
Fertilization	8.03	0.74	117.8	<0.001
Thinning	2.12	0.70	9.1	0.003
Fertilization:fertilized * Thinning:unthinned	2.85	1.19	5.7	0.02

Smooth terms

Variable	Interaction	k	EDF	F	p-value
Site index (temperature-detrended)		4	3.47	57.6	<0.001
Site index (temperature-detrended)	Unfertilized	4	1.04	1.0	0.32
Site index (temperature-detrended)	Fertilized	4	2.39	4.2	0.004
Stand age		4	3.78	120.4	<0.001
Stand age	Unfertilized	4	0.00	0.0	0.99
Stand age	Fertilized	4	3.28	15.5,	<0.001
Temperature sum 5		4	3.98	1113.1	<0.001
Temperature sum 5	Unfertilized	4	3.00	9.6	<0.001
Temperature sum 5	Fertilized	4	0.06	0.0	0.99
Stem density		4	3.98	309.8	<0.001
Stem density	Unfertilized	4	1.02	1.9	0.17
Stem density	Fertilized	4	1.17	1.2	0.43

The generalized additive model on spruce-dominated stands explained 69.8 % of the variation and all main effects were significant (Table 3). Fertilization did not interact significantly with thinning (Fig. 1). Similar to pine-dominated stands, standing tree volume increased with temperature sum, but did not level off as clearly as in pine-dominated stands (Fig. 2B), and increased with temperature-detrended site index (Fig. 2D). Fertilization interacted significantly with temperature-detrended site index, with no significant differences between fertilized and unfertilized stands at both ends of the site index range (i.e. below a temperature-detrended site index of −2.5 and above 9). This corresponds to stands with a site index below 15 in the north, and below 23 and above 35 in the south. In total 859 stands, or 8.0 % of the spruce-dominated stands in our data set, had a detrended site index below −2.5 or above 9, meaning they were not suitable for fertilization. In total 186 stands identified as unsuited for fertilization were, nevertheless, fertilized (accounting for 6.8 % of the fertilized spruce-dominated stands). Standing tree volume increased with stand age up to 100 years, after which it levelled of (Fig. 3B).

4. Discussion

We found that fertilized stands generally had a larger standing tree volume at harvest, but that the effect was context dependent. In pine-dominated stands, fertilization did not increase tree volume at harvest in stands with the lowest temperature sum, in the least productive stands, or in the youngest stands. In spruce-dominated stands, fertilization did not increase tree volumes at the lower and upper end of the site fertility gradient. The difference in average tree volume between fertilized and unfertilized pine-dominated stands (16.6–19.5 m^3 ha^{-1}) and spruce-dominated stands (13.9–18.4 m^3 ha^{-1}) is in line with growth responses to fertilization previously reported in pine (13–19 m^3 ha^{-1}) and spruce (14–21 m^3 ha^{-1}) (Saarsalmi and Mälkönen, 2001; Skogforsk, 2008). While the absolute difference in volumes between fertilized and unfertilized stands is quite similar for pine-dominated and spruce-dominated, the relative difference is greater for pine (+8.4–9.6 %, depending on thinning) than for spruce (+4.4–5.7 %, depending on thinning). Our results highlight that the effectiveness of fertilization varies across forest types, climate, and tree species. To enhance profitability and minimize the potential for undesired environmental impacts, more careful consideration should be given to selecting sites for fertilization. This is particularly important if the practice of forest fertilization is to become more widespread.

Spruce-dominated stands had much higher standing tree volumes than pine-dominated stands. This can partly be ascribed to differences in their distribution across the climatic and soil fertility gradients, with pine-dominated stands being more frequent in the colder regions and having a lower average site index. Still, even under similar conditions, spruce-dominated stands had higher standing tree volumes than pine-dominated stands. Studies using paired sites across Sweden (Leijon, 1979) and data from the Swedish national forest inventory (Ekö et al., 2008) suggested that spruce is more productive in southern Sweden and on fertile sites, while spruce and pine produce similar volumes in sites of intermediate fertility in central and northern Sweden. However, pine appeared to be most productive in the least fertile sites. Interestingly, this contrasts to experimental studies comparing monocultures of both species (Holmström et al., 2018; Nilsson et al., 2012), which suggested that pine is generally more productive than spruce. Worth noting is that these experiments were done in 52–82 years old stands, and also showed that the mean annual increase in spruce peaked at a much later stand age than for pine (Nilsson et al., 2012). Thus, whether spruce or pine is most productive depends on the growth stage considered. We observed a larger increase in tree volumes with stand age for spruce than for pine, especially in 50–100 year old stands.

We found no significant difference between fertilized and

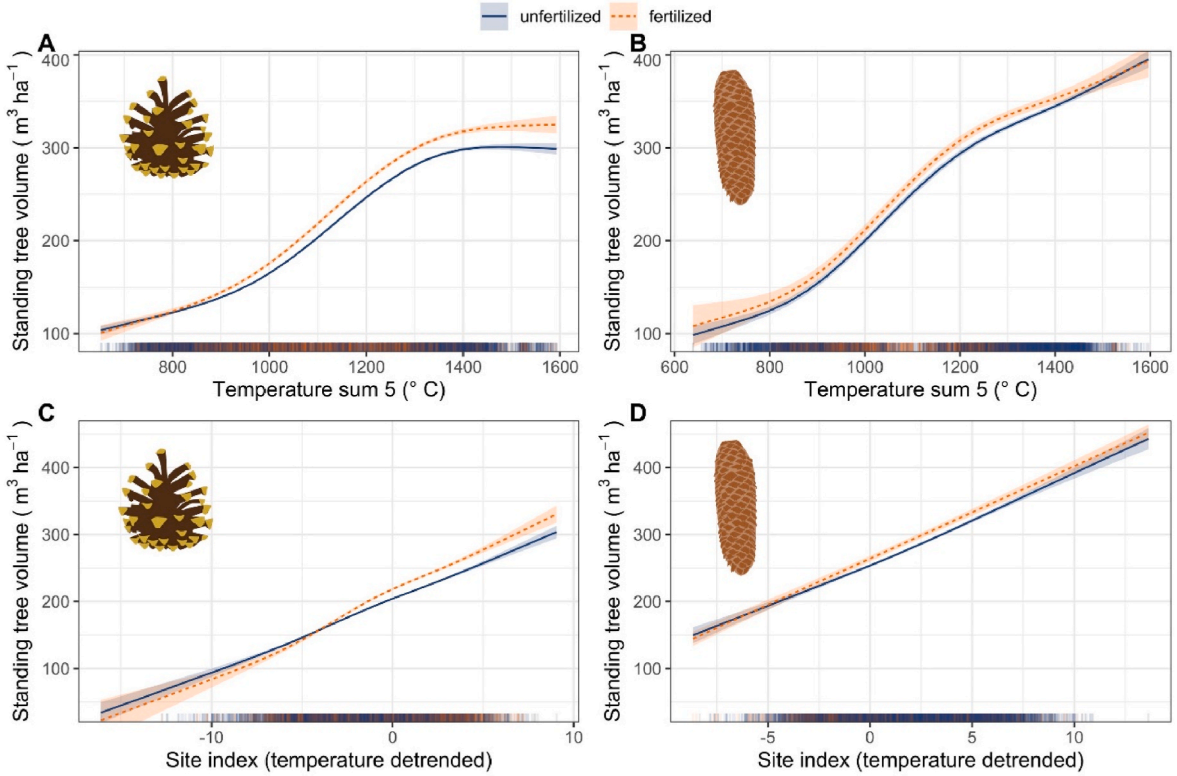

Fig. 2. Smooths from the generalized additive models on pine-dominated (A and C) and spruce-dominated (B and D) stands showing the variation in standing tree volume in fertilized and unfertilized stands across the temperature sum (A and B) and the temperature-detrended site index (C and D). These smooths are for the unthinned stands only, smooths for the thinned stands are very similar in shape, but with smaller differences between fertilized and unfertilized stands. Lines at the bottom indicate the distribution of the data points (coloured according to fertilization). Temperature sum 5 is the temperature sum of all days above 5 °C over 1 year.

unfertilized pine-dominated stands in low-fertile stands or in the coldest part of the study region, i.e. under the most nitrogen limited conditions (Du et al., 2020; Tamm, 1991). Similarly, we found no significant difference between fertilized and unfertilized spruce-dominated stands in low-fertile stands. This could potentially be caused by particularly strong nitrogen immobilisation belowground by soil microorganisms, such as ectomycorrhizal fungi, under strongly nitrogen limited conditions (Högberg et al., 2021; Kyaschenko et al., 2019; Näsholm et al., 2013). Using dual labelling with ^{15}N and ^{13}C, Näsholm et al. (2013) demonstrated that under nitrogen limited conditions, ectomycorrhizal fungi use a major fraction of the available nitrogen for their own growth. Similarly, Högberg et al. (2021) showed that growth of ectomycorrhizal fungi is nitrogen limited under nutrient-poor conditions, while carbon limited under nutrient-rich conditions. Organic matter originating from ectomycorrhizal mycelium has a long residence time in the soil and, thus, forms a strong nitrogen sink in the organic horizon (Kyaschenko et al., 2019). While Näsholm et al. (2013) found that ectomycorrhizal fungi, in the short term, increased nitrogen transfer to their host after fertilization, others have found that fertilization in the long term disfavours ectomycorrhizal fungi with prominent organic nitrogen-mining capacities (Jörgensen et al., 2022, 2024; Lindahl et al., 2021). With a large share of the added nitrogen locked up in mycelium and the ectomycorrhizal fungal communities shifted towards less efficient organic nitrogen-miners, fertilization in strongly nitrogen-limited environments could, from a long-term perspective, lead to reduced, rather than increased nitrogen uptake by the trees.

By using data from a major forest owner, we were able to gather a dataset that is much larger than could ever realistically be assembled through experiments. This large sample size makes our study unique and allows us to evaluate the effectiveness of operational forest fertilization. However, as this data was not collected with the goal of answering our research question, it also comes with some limitations. An important limitation is that we do not have data on the extracted volumes during thinning, which could obscure the fertilization effect in thinned stands. Furthermore, working with data that is collected for the purpose of maintaining forestry practices, means that the ‘treatments’ we study have not been applied in a standardised way, creating noise in our dataset.

Despite its limitations, our study advances the understanding of the context-dependency of fertilization effects on tree volume, potentially leading to improved sustainability in forest management. To reduce the negative effects of forest fertilization while simultaneously increasing the revenue for the forest owner, and promoting the carbon uptake by forests, we suggest that the context dependency of fertilization effects should be more carefully considered. We propose that pine-dominated stands in regions with cold climate, in our case those with temperature sum 5 below 800 °C, should not be fertilized. Likewise, we propose that pine-dominated sites situated on land in the lower end of the fertility range, in our case site index lower than 14 or 22 in northern and southern Sweden, respectively, should also be exempted from fertilization. For spruce-dominated stands, we propose that stands with a site index below 15 in northern Sweden, and below 23 and above 35 in the southern Sweden, should not be fertilized. In our dataset, this implies that fertilization has little effect on 21.3 % of the pine-dominated stands and 8.0 % of the spruce-dominated stands. This also implies that 17.0 % of the fertilized pine-dominated stands and 6.8 % of the fertilized spruce-dominated stands included in our study should not have been fertilized. In these stands, fertilization probably had a negative impact on biodiversity, while having no significant effect on tree productivity, and thus ended up as costly both in terms of profitability and sustainability.

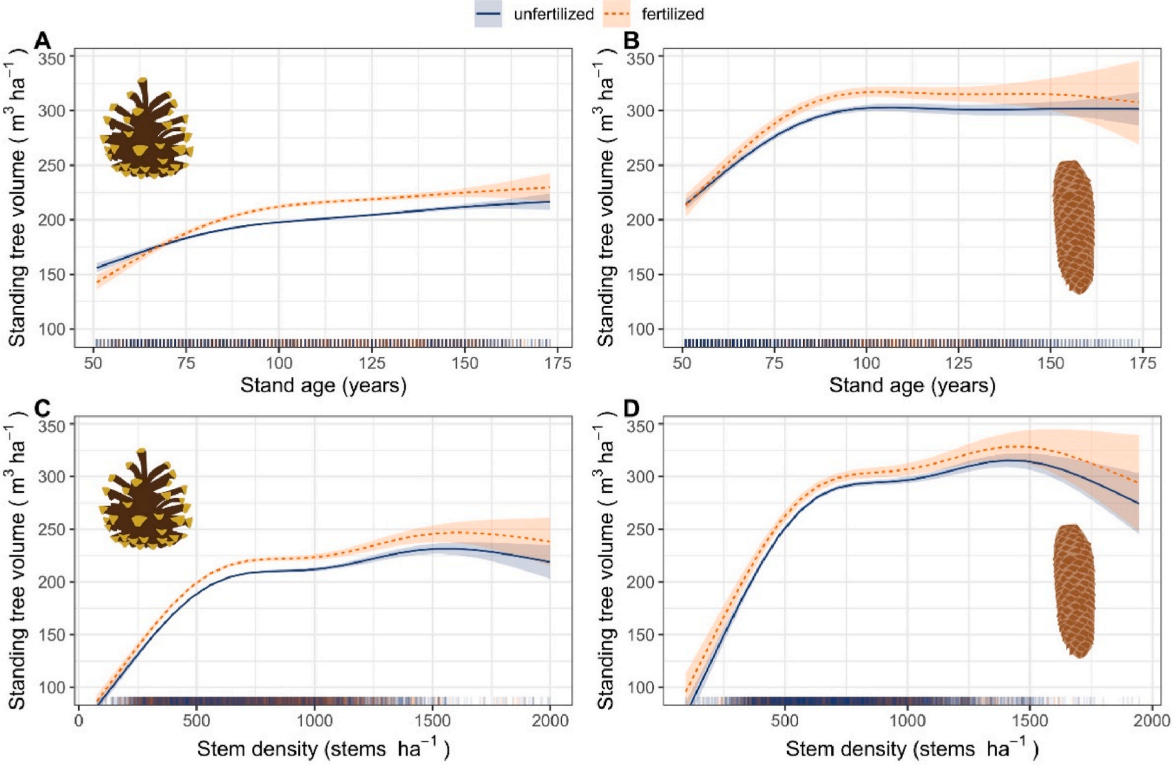

Fig. 3. Smooths from the generalized additive models on pine-dominated (A and C) and spruce-dominated (B and D) stands estimating the variation in standing tree volume in fertilized and unfertilized stands across stand age (A and B) and stem density (C and D). These smooths are for the unthinned stands only, smooths for the thinned stands are similar in shape but with smaller differences between fertilized and unfertilized stands. Lines at the bottom indicate the distribution of the data points (coloured according to fertilization).

Table 3
Outcome of the generalized additive model on the spruce-dominated stands ($R^2_{adj} = 0.698$, n = 10,638). k: number of basis functions, EDF: estimated degrees of freedom, temperature sum 5: temperature sum of all days above 5 °C, accumulated over 1 year.

Parametric terms					
Variable	Estimate		Standard Error	F	p-value
Fertilization	5.92		1.70	12.2	<0.001
Thinning	2.98		1.38	4.6	0.03
Fertilization:fertilized * Thinning: unthinned	4.67		2.84	2.7	0.10
Smooth terms Variable	Interaction	k	EDF	F	p-value
Site index (temperature-detrended)		4	1.00	365.4	<0.001
Site index (temperature-detrended)	Unfertilized	4	1.47	3.7	0.02
Site index (temperature-detrended)	Fertilized	4	1.01	0.8	0.36
Stand age		4	3.89	131.2	<0.001
Stand age	Unfertilized	4	1.00	0.2	0.66
Stand age	Fertilized	4	1.62	1.9	0.11
Temperature sum 5		4	3.95	90.1	<0.001
Temperature sum 5	Unfertilized	4	1.00	1.2	0.27
Temperature sum 5	Fertilized	4	1.30	2.4	0.18
Stem density		4	3.95	139.3	<0.001
Stem density	Unfertilized	4	0.97	0.7	0.54
Stem density	Fertilized	4	1.01	0.2	0.69

CRediT authorship contribution statement

Margaux Boeraeve: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Gustaf Granath:** Writing – review & editing, Methodology, Conceptualization. **Björn D. Lindahl:** Writing – review & editing, Methodology, Conceptualization. **Karina E. Clemmensen:** Writing – review & editing. **Joachim Strengbom:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.124023.

Data availability

The authors do not have permission to share data.

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