

# Trade-offs in the multi-use potential of managed boreal forests

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## Abstract

1. Implementing multi-use forest management to account for both commercial and non-commercial ecosystem services is gaining increased global recognition. Despite its spatial extent, and great economic and ecological values, few studies have evaluated the boreal forest and its management to assess the potential for simultaneous delivery of a suite of ecosystem services.
2. Using data from a Swedish long-term experiment, this study explores how biodiversity of the ground vegetation and potential delivery of multiple ecosystem services (timber production, carbon [C] storage and non-timber forest products) are influenced by two common silvicultural practices (thinning, fertilization and their interaction).
3. Diversity (diversity indices and species richness) of the ground vegetation was higher in thinned than in unthinned forest, a result attributable in part to six species of lichens that only occurred in thinned forest. In addition, supply of lichens for reindeer forage was three times higher in thinned forest. Fertilization negatively affected the lingonberry shrub (*Vaccinium vitis-idaea*). Timber production increased with fertilization, but decreased with thinning. The potential for C storage was highest in fertilized forests, which, apart from having the highest timber production, also supported the highest standing tree biomass.
4. The silvicultural practices evaluated induced trade-offs among the ecosystem features studied as thinning increased biodiversity of the ground vegetation, production potential of wild berries and lichens, but reduced timber production and the potential for C storage. Fertilization had the opposite effect, promoting the potential for C storage at the expense of biodiversity and the ecosystem services delivered by the ground vegetation.
5. *Synthesis and applications.* Increased multi-use potential is a common goal for forest management in many parts of the world. Our result shows that commonly used silvicultural practices can be used to determine the multi-use output, and might be applied to maintain, or even increase the multi-use potential of the boreal forest biome. Nevertheless, trade-offs among values were common, indicating that the multi-use potential will be limited at the site level. Allowing management objectives to vary across the landscape might, in such cases, be a preferable way to achieve high multi-use potential.

## KEYWORDS

biodiversity, carbon storage, climate change, forest use, multi-use, non-timber forest products, reindeer forage, silvicultural, sustainable forest management, timber production

## 1 | INTRODUCTION

Increased appreciation of the multiple services provided by ecosystems (Bennett, Peterson, & Gordon, 2009; Gamfeldt et al., 2013) highlights a need for forest management that looks beyond wood production to consider a wealth of ecosystem services. Beside preservation of biodiversity, this includes services such as delivery of non-timber forest products (NTFPs; Duchesne & Wetzel, 2002; Ticktin, 2004) and the potential for climate change mitigation through increased carbon (C) storage in living biomass, soils and litter (Bonan, 2008; Lundmark et al., 2014). A key challenge in such agendas is to determine how various silvicultural practices influence forest biodiversity and the broad suite of functions and services that the forest can provide (Berch, Morris, & Malcolm, 2011).

Development of multi-use options for the boreal forest could be of major global significance given that this region constitutes the largest terrestrial biome, covering much of Canada, Russia and Fennoscandia. Although large parts of the biome are pristine forests and subjected to only low-intensity forestry, the increasing demand for forest-related products calls for a better understanding of how intensified forestry influences the delivery of alternative goods and services from boreal forests. In the boreal forest, Fennoscandia has the longest history of active forest management, making this region suitable for addressing how the multi-use potential of less intensively managed boreal forests may be affected by an expanded and intensified forestry.

In Fennoscandia, silvicultural practices including thinning and fertilization are applied to enhance the production of commercially marketable assortments, and are both part of the common forest management strategy. Although the influence of thinning and fertilization on wood production is well documented in the boreal coniferous forests (e.g. Bergh, Nilsson, Allen, Johansson, & Fahlvik, 2014), their simultaneous effects on alternative services, or their effects on multiple ecosystem services, remain unexplored. Apart from affecting tree growth, these practices influence other aspects of the ecosystem. For example, thinning increases the availability of light and thus growth of the ground vegetation (Bartemucci, Messier, & Canham, 2006), with subsequent effects on the composition of plant species (Bartemucci et al., 2006; Burton, Ares, Olson, & Puettmann, 2013; Hedwall, Strengbom, & Nordin, 2013).

Besides contributing to the overall forest biodiversity, the ground vegetation is also important for ecosystem functioning, as its composition can influence forest nutrient dynamics and successional development (Wardle et al., 2012). As for thinning, fertilization also influences ground vegetation by interfering with interspecific competitive interactions, promoting the growth of fast-growing graminoids and herbs at the expense of slow-growing species such as berry-producing dwarf shrubs (Strengbom & Nordin, 2008). Hence, the potential to harvest wild berries, such as bilberries and lingonberries, can be influenced by the silvicultural practices applied (Kardell, 1980; Miina, Pukkala, Hotanen, & Salo, 2010; Saastamoinen, Kangas, & Aho, 2000). Despite the potentially high revenue that berry production represents (Miina et al., 2010), few studies have addressed the single and combined

effects of thinning and fertilization on the potential of forests to produce berries.

In northern areas of Fennoscandia, reindeer husbandry is an important type of land use, and as reindeers depend on lichens for forage during winter (Kivinen, Moen, Berg, & Eriksson, 2010), lichen availability is an important ecosystem service. Both thinning and fertilization influence productivity and composition of lichen communities (e.g. Cabrajic, Moen, & Palmqvist, 2010; Strengbom, Nordin, Näsholm, & Ericson, 2001), and choice of silvicultural practice may therefore influence the delivery of the ecosystem services that lichens represent.

In addition to these values, thinning and fertilization can influence the C storage potential of the forest. Although thinning often increases tree growth in the remaining trees, the removal of biomass often results in a net reduction of C storage (Bergh et al., 2014; Burton et al., 2013; Nunery & Keeton, 2010). Fertilization can increase C storage both by increasing standing biomass and lowering heterotrophic soil respiration (Bergh et al., 2014; Hyvönen et al., 2008).

In this study, we address the influence of forest management on the multi-use potential of managed pine forests in Sweden. We consider the effects of five silvicultural practices: thinning, no thinning (NoTh), NoTh combined with fertilization with nitrogen (N), thinning combined with fertilization with N and thinning combined with fertilization with N and phosphorus (P). We estimate the multi-use potential by considering four basic characteristics of the ecosystem: (1) biodiversity of the ground vegetation (i.e. richness and composition of vascular plants, bryophytes and lichens); (2) delivery of NTFPs based on the potential of the ground vegetation to produce wild berries and lichens suitable for reindeer forage; (3) timber value expressed as stem wood production; and finally (4) potential for C storage, based on the standing biomass of above- and below-ground parts of the vegetation. Based on studies conducted in other ecosystems, we hypothesized that: (1) thinning promotes biodiversity (Burton et al., 2013), but reduces timber production and ecosystem C storage (Burton et al., 2013; Nunery & Keeton, 2010), and that (2) fertilization enhances timber production and ecosystem C storage (Bergh et al., 2014), but hampers delivery of NTFPs and species diversity (Strengbom et al., 2001).

## 2 | MATERIALS AND METHODS

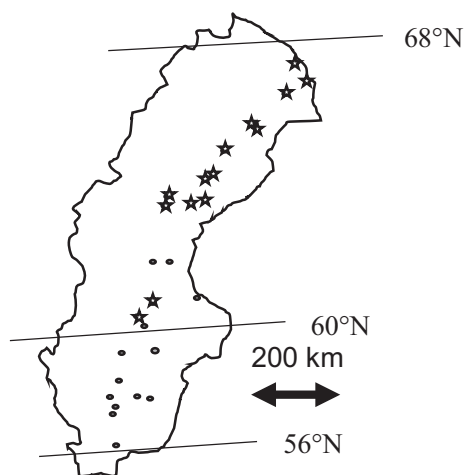
### 2.1 | Experimental setup

For our study, we used an already established long-term field experiment including 117 field-plots (0.1 ha with a 10 m buffer zone) distributed throughout 27 sites sampling the boreal zone of Sweden (Figure 1). The experiment was established between 1966 and 1981 in uniform and even aged monocultures of Scots pine (*Pinus sylvestris* L.). The practices included, not replicated within sites, were: thinning (Th), NoTh, NoTh in combination with N fertilization (N), thinning in combination with N fertilization (Th+N) and thinning in combination with N and P fertilization (Th+N+P). The first thinning was conducted when the experimental plots were established and the trees were between 12 and 16 m high (depending on the location 32–54 years old)

and reduced the basal area 25%, on average, to c. 18 m<sup>2</sup>/ha. The subsequent two thinnings removed the growth between thinnings, so that the basal area following each thinning was returned to c. 18 m<sup>2</sup>/ha. Nitrogen fertilization corresponded to an addition of 100 kg N/ha per fertilization event for northern locations (above latitude 61) and 150 kg N/ha per fertilization event for southern locations (below latitude 61), and was initiated the year following the first thinning and was repeated every fifth year during the first 25 years, and thereafter every seventh year. The higher N addition in the south was intended to match higher productivity at southern sites, that is, striving towards a N addition rate somewhat proportional to the putative internal N cycling. The phosphorus treatment, which was only applied in combination with thinning and N fertilization, corresponded to 100 kg P/ha, and was initiated at the same time as the N fertilization, and then repeated after 21 or 22 years. Nitrogen was added as ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>) and phosphorus as superphosphate (CaSO<sub>4</sub> + Ca(H<sub>2</sub>PO<sub>4</sub>)<sub>3</sub>). The timing of the experimental manipulations differed among sites to follow the stand development at each site, whereas all manipulations within a site were conducted at the same occasion. For more details on the treatments and descriptive site data see Table S1.

## 2.2 | Sampling

The ground vegetation was surveyed during the summers of 2009 and 2010. Firstly, we collected point-intercept data at 140 random positions along two 30-m transects placed diagonally in each plot. At each position, we penetrated the vegetation with a stick (∅ = 4 mm) noting the number of times that each species intercepted the stick (for lichens and bryophytes only one contact per species and position). Secondly, we estimated above-ground biomass of the ground vegetation by harvesting all above-ground plant material in five circular subplots (∅ = 25 cm) distributed at 5-m intervals along each of the aforementioned transects. After harvest, the plant material was brought to the laboratory for sorting and dried to a constant mass.



**FIGURE 1** Map showing Sweden and location of the 27 experimental sites. Sites used to assess effect on the potential for reindeer grazing are denoted with stars

## 2.3 | Formulation of the forest multi-use response variables

To estimate the forest's multi-use potential we used several measures. Effects on biodiversity were estimated by the response of the ground vegetation. Besides species composition and species richness, based on the point-intercept data, we calculated Simpson's inverse diversity index  $D$  as  $(\frac{1}{d} = \frac{1}{\sum_{i=1}^S p_i^2})$ , and Shannon's  $H$  index as  $H = -\sum_{i=1}^S p_i \ln(p_i)$  (where  $P_i$  is the proportion of the  $i$ th species and  $S$  is the number of species in the community) and their corresponding evenness measures. Effects on the delivery of NTFPs were estimated as the potential for reindeer grazing and production of wild berries based on the biomass of ground-living lichens and biomass of berry-producing ericaceous dwarf shrubs (*Vaccinium vitis-idaea* L. and *Vaccinium myrtillus* L.). When assessing the potential for reindeer grazing, we only included sites located in counties where winter reindeer grazing is practiced (Figure 1). We used the biomass of berry-producing shrubs as a proxy for berry production because previous studies indicate that berry production is correlated with plant cover/biomass (Miina et al., 2010) and that it produces an indicative directional estimate of the response to fertilization and thinning (Granath & Strenghom, 2017).

Timber production was assessed as the average annual stem wood growth, over the experimental period, calculated as the summed stem wood production, including the production that was removed during thinning. Growth was calculated based on the functions developed by Brandel (1990) using measurements of diameter at breast height (1.30 m above-ground; DBH), tree height and bark thickness recorded for all trees when the experiment was initiated, at the time of every thinning, and at irregular intervals between the thinning operations. For more details, see Bergh et al. (2014). Data for timber production were derived from 20 of the total 27 sites, that is,  $n = 20$ , with the exception of N fertilization ( $n = 9$ ) and Th+N+P ( $n = 18$ ).

The potential for C storage was estimated from the above- and below-ground standing biomass of trees and ground vegetation. Tree biomass derived from DBH and tree height using biomass functions (roots, stems, branches and needles) for Scots pine (Marklund, 1988). For the ground vegetation, total standing biomass was estimated from the harvested biomass. The below-ground biomass was estimated from above-ground biomass using root:shoot ratios of three dominant species (97% of the total above-ground field-layer biomass: *V. vitis-idaea* 30%, *V. myrtillus* 58%, and grasses 9%). We used root:shoot ratios (*V. vitis-idaea* [1.0], *V. myrtillus* [4.5] and the grass *Deschampsia flexuosa* (L.) Trin. [2.6]) derived from Nordin, Näsholm, and Ericson 1998. Data on ground vegetation were derived from the full set of experimental plots, that is,  $n = 27$  except for N fertilization that was replicated at nine sites. Data on tree biomass were derived from 20 of the total 27 sites, that is,  $n = 20$ , with the exception of N fertilization ( $n = 9$ ) and Th+N+P ( $n = 18$ ).

## 2.4 | Statistics

The variables described above were analysed by ANOVA with the main factor "practice" as categorical explanatory variable including "site" as a random blocking factor to account for variability among

the sites. To control for the variation generated by positions along the geographical gradient and time since thinning, we included site latitude and time since last thinning operation as fixed factors in our analyses. To clarify whether the N effect on productivity differed depending on latitude, we ran a separate analysis on timber production including only N treatment, latitude and their interaction. Data were checked for deviations from assumptions of normality and equal variances among groups using residual plots and histograms. When deviations occurred the data were  $\log(x + 1)$  transformed before analyses. Significant effects were subsequently explored using Tukey's HSD post hoc test in order to identify differences among the five different silvicultural practices. To explore the potential trade-off among values, we conducted planned contrasts (by Tukey's HSD post hoc tests) and compared differences related to the thinning treatment, which is considered to be the standard practice.

We used canonical analysis of the point-intercept data to illustrate treatment-induced differences in the composition of the ground vegetation. To reduce the influence of rare and uncommon species we only included data from the 10 most abundant species (still representing 95% of all observations). Discriminant analyses using Wilks' lambda were used to test for significant differences among the canonical means of the different treatments. Significant effects among practices were explored with confidence ellipses (95%) around canonical means in which non-overlapping ellipses explain the significant difference found in discriminant analyses. All statistical analyses were conducted using JMP Pro 11.

### 3 | RESULTS

#### 3.1 | Ground vegetation

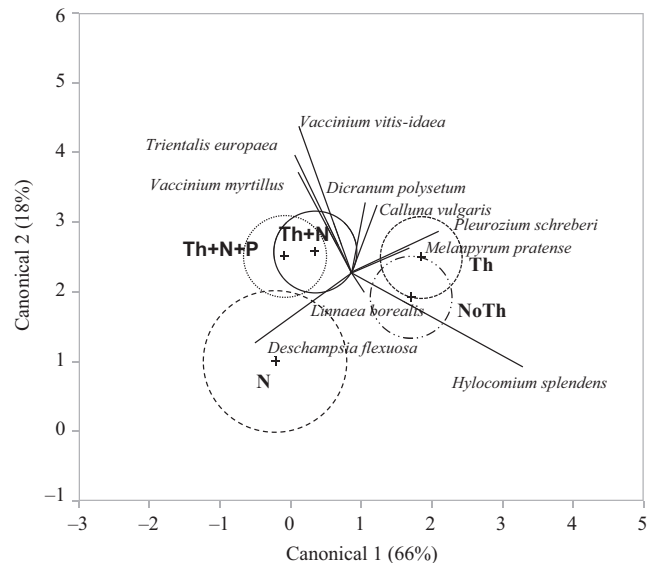
Multivariate analyses of the point-intercept data revealed that species composition varied according to silvicultural practice (Wilks'  $\lambda$   $F = 2.72$ ,  $p < .0001$ ; Figure 2). This was mainly generated by a contrasting species composition between the NoTh practice and the practices including fertilization (N, Th+N, Th+N+P; Figure 2). This contrast was mainly caused by the higher abundance of the grass *Deschampsia flexuosa* in the practices including fertilization, and lower abundance of the feathermoss *Hylocomium splendens* (Hedw.) Schimp. in the NoTh practice (Figure 2). Higher abundances of the two dwarf shrubs *V. vitis-idaea* and *V. myrtilus*, and the herb *Trientalis europaea* L. in the practices including both thinning and fertilization (Th+N and Th+N+P) also contributed to the pattern (Figure 2).

Differences in composition of the ground vegetation among practices reflected differences in both species richness ( $F_{4,86.47} = 5.57$ ,  $p = .0005$ ) and to differences in the dominance structure among species. The latter was caused by significant effects on diversity indices (Simpson's  $D$ :  $F_{4,87.5} = 3.87$ ,  $p = .0061$ ; Shannon's  $H$ :  $F_{4,88.9} = 7.17$ ,  $p < .0001$ ; evenness:  $F_{4,86.7} = 6.25$ ,  $p = .0002$ ). The Th+N+P practice had higher species richness than the unthinned practices (N and NoTh), and Th+N had higher species richness than the NoTh (Tukey's HSD  $p < .05$ ), while other practices were intermediate (Table 1). Shannon's  $H$  values were higher under Th than under N and Th+N, and the N was lower than Th+N+P and NoTh (Table 1). The corresponding evenness

was highest for Th and lowest for N, and Th had significant higher evenness than all practices including N (N, Th+N and Th+N+P), and the N treatment had lower evenness than the NoTh (Table 1). Simpson's  $D$  values were significantly lower under the N treatment than under Th, whereas other practices were intermediated. For the corresponding evenness, there were no significant differences among practices (Table 1). Species richness ( $F_{1,28.5} = 5.25$ ;  $p = .030$ ) and Shannon  $H$  ( $F_{1,25.2} = 4.20$ ,  $p = .051$ ) increased with increasing latitude, while other indices were unaffected by latitude. Time since last thinning had no significant effect on any of the diversity measures. A full list of all species recorded in the different treatments is provided in Table S2.

#### 3.2 | Potential for NTFPs

The potential for delivery of NTFPs differed among practices (bilberry:  $F_{4,85.6} = 2.45$ ,  $p = .053$ ; lingonberry:  $F_{4,89.2} = 13.24$ ,  $p < .0001$ ; lichens:  $F_{4,43.3} = 5.29$ ,  $p = .0015$ ; Figure 3). Lichen biomass was higher in thinned than in unthinned plots, and always negatively affected by N fertilization (Tukey's HSD  $p < .05$ ; Figure 3). The effect on bilberry shrub biomass was generally small, with no differences among practices (Figure 3). Lingonberry shrub biomass responded negatively to N fertilization (Tukey's HSD,  $p < .05$ ), but the negative effect of N fertilization was absent when fertilization was combined with thinning (Th+N; Figure 3). The positive thinning effect was, however, lost when also P was added together with N, and the Th+N+P practice had lower



**FIGURE 2** Two-dimensional canonical ordination showing community composition of the ground vegetation under five silvicultural practices: Thinning (Th), No thinning (NoTh), N fertilization (N), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). Non-overlapping confidence ellipses (95%) around canonical means indicate a significant difference in discriminant analyses (Wilks'  $\lambda$   $F = 2.72$ ,  $p < .0001$ ). Biplot rays represent the response (strength and direction) of the 10 most abundant forest floor species in relation to the silvicultural practices. Percentages on the canonical X and Y axes represent the amount of variation explained by the respective axes

**TABLE 1** Diversity measures on the ground vegetation showing species richness, Shannon's and Simpson's indices and their corresponding evenness measures in response to the five silvicultural practices: Thinning (Th), No thinning (NoTh), N fertilization (N), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). Data presented are model estimates  $\pm$  SE. Values with different letters indicate significant differences in pair-wise comparisons (Tukeys HSD  $p < .05$ )

Silvicultural practice	Species richness	Shannon's $H$	Shannon's evenness	Simpson's $D$	Simpson's evenness
Thinning (Th)	12.2 $\pm$ 0.5 <sup>abc</sup>	1.7 $\pm$ 0.05 <sup>a</sup>	0.68 $\pm$ 0.02 <sup>a</sup>	4.2 $\pm$ 0.2 <sup>a</sup>	0.35 $\pm$ 0.02 <sup>a</sup>
No thinning (NoTh)	10.8 $\pm$ 0.5 <sup>c</sup>	1.5 $\pm$ 0.05 <sup>ab</sup>	0.65 $\pm$ 0.02 <sup>ab</sup>	3.5 $\pm$ 0.2 <sup>ab</sup>	0.34 $\pm$ 0.02 <sup>a</sup>
N fertilized	10.4 $\pm$ 0.8 <sup>bc</sup>	1.2 $\pm$ 0.08 <sup>c</sup>	0.53 $\pm$ 0.03 <sup>c</sup>	2.8 $\pm$ 0.3 <sup>b</sup>	0.29 $\pm$ 0.03 <sup>a</sup>
Th+N	12.3 $\pm$ 0.5 <sup>ab</sup>	1.5 $\pm$ 0.05 <sup>b</sup>	0.61 $\pm$ 0.02 <sup>bc</sup>	3.5 $\pm$ 0.2 <sup>ab</sup>	0.30 $\pm$ 0.02 <sup>a</sup>
Th+N+P	13.0 $\pm$ 0.5 <sup>a</sup>	1.5 $\pm$ 0.05 <sup>ab</sup>	0.61 $\pm$ 0.02 <sup>bc</sup>	3.7 $\pm$ 0.2 <sup>ab</sup>	0.30 $\pm$ 0.02 <sup>a</sup>

lingonberry shrub biomass than the Th+N practice (Figure 3). Biomass of lingonberry increased with time since last thinning ( $F_{1,32.4} = 10.80$ ,  $p = .0024$ ) and latitude ( $F_{1,28.6} = 12.84$ ,  $p = .0012$ ), while no such effects were noticed for biomass of bilberry or lichen ( $p > .11$  for all).

### 3.3 | Timber production

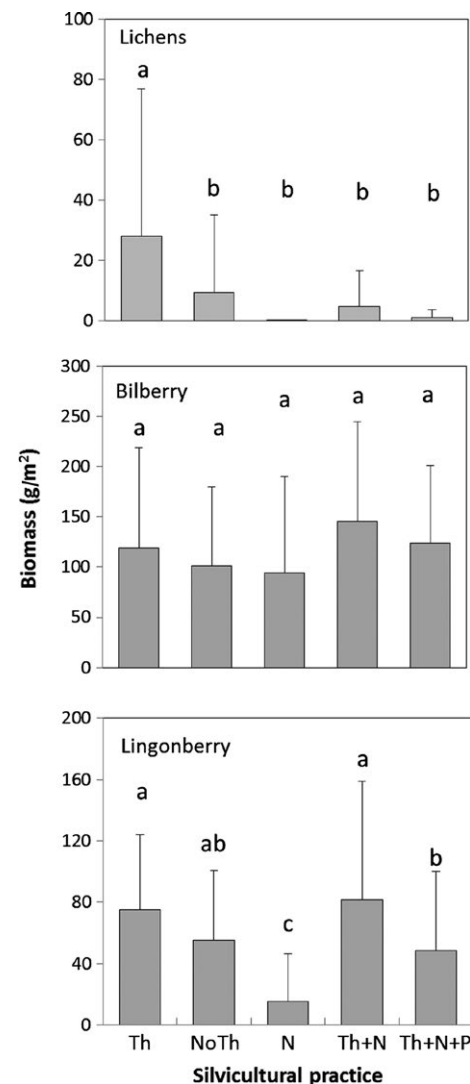
Timber production (stem growth) differed among treatments ( $F_{4,83.3} = 28.31$ ,  $p < .0001$ ; Figure 4), but was unaffected by time since last thinning and latitude ( $p > .5$  for both). Despite a clear positive N effect, the effect was not influenced by latitude (N  $\times$  latitude:  $F_{1,65.8} = 0.0003$ ,  $p = .99$ ). The Th practice had the lowest production, while the N practice had the highest production (Tukey's HSD  $p < .05$ , Figure 4). Also, the NoTh practice had higher production than Th (Tukey's HSD  $p < .05$ ; Figure 4). The Th+N and the Th+N+P practices resulted in higher production than the NoTh practice, but lower than the N practice (Tukey's HSD  $p < .05$ ; Figure 4).

### 3.4 | Potential for C storage

Standing biomass differed among practices (total:  $F_{4,63.4} = 88.76 < 0.0001$ ; tree:  $F_{4,63.5} = 96.78$ ,  $p < .0001$ ; ground vegetation:  $F_{4,87.0} = 5.67$ ,  $p = .004$ ; Figure 5). Time since last thinning and latitude had no effect ( $p > .58$  for all tests). The response of standing biomass was mainly reflected by the response of tree biomass (Figure 5), and for both total and tree biomass, practices that did not include thinning (NoTh and N) had a higher biomass than those including thinning (Tukey's HSD  $p < .05$ ; Figure 5) and the N practice resulted in a higher standing tree biomass than the NoTh one (Tukey's HSD  $p < .05$ ; Figure 5). The biomass of the ground vegetation was higher (Tukey's HSD  $p < .05$ ) in the Th+N practice than in practices that were not thinned (NoTh and N; Figure 5). The other practices were intermediate and did not differ from the aforementioned ones (Figure 5).

## 4 | DISCUSSION

Thinning and fertilization had contrasting effects on the alternative forest values and ecosystem services considered, and trade-offs were frequent. This demonstrates that intensified use of the boreal biome for forestry purposes will influence the delivery of alternative values



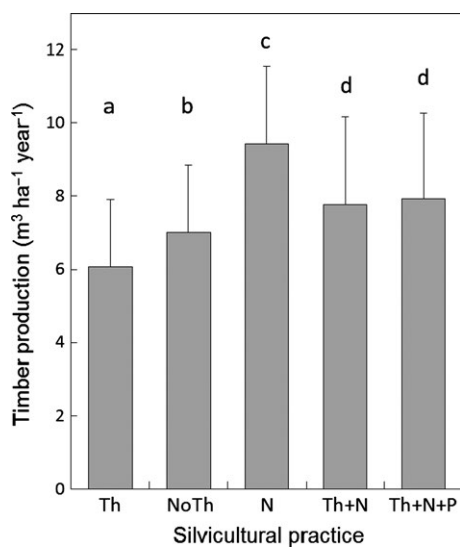
**FIGURE 3** Potential for production of non-timber forest products (NTFPs) under five silvicultural practices: Thinning (Th), No thinning (NoTh), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). The potential for NTFPs are expressed as above-ground biomass (dry weight) of ground-living lichens, bilberry shrubs (*Vaccinium myrtillus*), and lingonberry shrubs (*Vaccinium vitis-idaea*). Bars denoted with different letters indicate significant difference in pair-wise comparisons based on model estimates (Tukey's HSD  $p < .05$ ). Error bars are SD

to those traditionally sought by the forest industry. The observed trade-offs also demonstrate that silvicultural practices can be used to determine delivery of individual ecosystem services, as well as to adjust the multi-use potential. Although our study may help in overcoming some of the obstacles that hamper the development of multi-use management options, the identified trade-offs suggest that high multi-use can be difficult to achieve on the stand level. However, with clearly defined management objectives that vary among stands across a landscape, the delivery of multiple ecosystem services from forest landscapes can be promoted.

#### 4.1 | Diversity of ground vegetation

We show that thinning promotes biodiversity of the ground vegetation primarily by influencing species richness (primarily by increasing lichen richness), whereas N fertilization impedes it, through a changed dominance hierarchy of the community. Studies examining the combined effects of these silvicultural practices are not common, but our results are in accordance with the finding that thinning can promote understorey species richness (Burton et al., 2013) and modify plant community response to N additions (Hedwall et al., 2013).

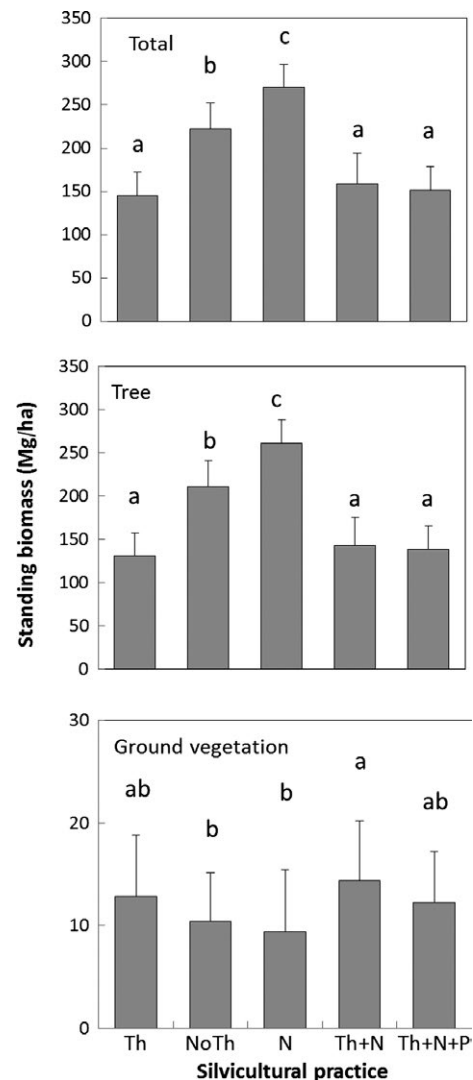
Our results suggest that thinning generates conditions that not only promote lichen growth, as suggested by others (e.g. Cabrajic et al., 2010), but also generates conditions favouring species richness of lichens. Nitrogen fertilization, on the other hand, generates stand conditions that are clearly negative for lichens. In contrast to the response of the lingonberry shrub, for which the negative effect of N fertilization was counteracted by thinning, the negative effect of fertilization



**FIGURE 4** Forest timber production under five different silvicultural practices: Thinning (Th), No thinning (NoTh), N fertilization (N), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). Data represent mean annual stem volume increment (m<sup>3</sup>/ha) of Scots pine stands over a 22–41-year period. The volume increment includes both the increment left in the forest and the volume removed through thinning. Bars denoted with different letters are significantly different (Tukey's HSD,  $p < .05$ ). Error bars are SD

on lichens was not mitigated by thinning. We suggest that negative effects on lichens, stem from intensified light competition, originating from denser tree canopy cover under unthinned conditions, and from denser dwarf shrub cover under thinned and N-fertilized conditions.

The main responses induced by N fertilization on the ground vegetation were increased abundance of the grass *D. flexuosa* and decreased abundance of the bryophyte *H. splendens*, which confirms results of earlier studies (Strengbom & Nordin, 2008; Strengbom et al., 2001). Not surprisingly, thinning favoured light-demanding species, for example, *Calluna vulgaris* (L.) Hull and *Pleurozium schreberi* (Brid.) Mitt, over those typically associated with the darker conditions of later successional forest stages, for example, *Linna borealis* L. and *H. splendens*. Our results are, thus, in accordance with studies suggesting that



**FIGURE 5** Standing plant biomass (above- and below-ground) under five silvicultural practices: Thinning (Th), No thinning (NoTh), N fertilization (N), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). The biomass pools are standing total biomass, standing tree biomass and standing biomass of the ground vegetation. Bars marked with different letters indicate significant differences in post hoc comparisons based on modelled estimates (Tukey's HSD,  $p < .05$ ). Error bars are SD

thinning can prevent the successional development associated with older and darker forest stands (e.g. Burton et al., 2013). Interestingly, however, our results show that thinning can alleviate some of the negative effects that fertilization imposes on the ground vegetation. Although thinning could not prevent all changes, such as altered species composition, thinning appeared to maintain species richness and enable the berry-producing dwarf shrubs to maintain their dominant position, and thereby prevent expansion of grasses. This is in accordance with Strengbom, Nordin, Näsholm, and Ericson (2002) suggesting that N-induced changes in the ground vegetation can be kept at bay as long as the dwarf shrubs can maintain their dominant position. It is noticeable that the ground vegetation in our experiment included very few, if any, species of direct conservation concern. Thus, the effects we describe are more relevant for maintaining ecosystem functioning, for example, such as dominant trophic interactions and nutrient dynamics (Strengbom et al., 2002; Wardle et al., 2012) than preservation of certain species per se. Nevertheless, this calls into question the efficiency of thinning as a tool to counteract unwanted effects of increased N input, that is, to what extent thinning can be used as a management tool to counteract negative effects of N deposition on forest diversity?

#### 4.2 | Delivery of NTFPs

Currently, management with the objective of improving the delivery of NTFPs is not commonly practiced in boreal forests, but this may change as many NTFPs in the future may receive greater recognition. Our study demonstrates that conventional silvicultural practices can be used to improve delivery of NTFPs, if that is desired. Scandinavian reindeer husbandry is dependent on lichens as these constitute important winter forage. Conflicts between reindeer husbandry and commercial forestry are common, as many common forestry practices like clear-felling and soil scarification may reduce the abundance of lichens (Kivinen et al., 2010). Developing management schemes that consider both lichen and timber production may thus be needed in areas used for reindeer husbandry. Earlier studies suggest that a canopy cover above 60% hampers lichen growth (Cabrajic et al., 2010). Our study shows that thinning increased lichen biomass more than threefold, suggesting that thinning can be used as a management tool to improve forests as foraging grounds for reindeer.

Even though the production of wild berries represents a significant value of boreal forests (Kardell, 1980; Saastamoinen et al., 2000), berry yield is not a targeted aim of current forest management. The situation may, however, change in the future due to an increasing demand for berries from the growing industrial production of berry-based “functional foods”. Our study demonstrates that silvicultural practice can be used to promote the production potential of wild berries. Thinning has previously been suggested as a measure to promote the abundance of bilberry and lingonberry shrubs (Kardell, 1980; Raatikainen et al., 1984), and hence the potential for economic revenue from berries (Miina et al., 2010). Despite the lack of a thinning effect, biomasses of both bilberry and lingonberry shrubs were lowest when standing tree biomass was highest, suggesting that high tree canopy cover hampers productivity of these dwarf shrubs. Furthermore, we found

that the negative response to N fertilization was alleviated when it was combined with thinning. For bilberry, combining thinning and N fertilization resulted in the overall highest shrub biomass. Altogether, this suggests that high productivity of these dwarf shrubs is not solely driven by light availability, but rather by high N availability in combination with the improved light availability that follows thinning.

#### 4.3 | Timber production and climate change mitigation

Our study shows that both timber production and standing tree biomass decreased following thinning, but increased with N fertilization. This is well in line with other studies of tree growth responses to N fertilization (Bergh et al., 2014) and thinning (Burton et al., 2013; Nunery & Keeton, 2010). In our study, practices that included thinning resulted in lower timber production. This does not necessarily mean that thinning is unfavourable for the forest owner, as it provides income at a regular basis and can positively influence timber quality and thereby the value of the timber produced.

In addition to the traditional value that timber production represents, the possibility for managing forests for climate change mitigation is gaining increased attention (Canadell & Raupach, 2008; Paquette & Messier, 2010). A managed forest can provide a large amount of sustained biomass yield while at the same time maintaining large forest C stocks, and by this mitigate climate change by reducing net emissions of C to the atmosphere (Canadell & Raupach, 2008). The climatic benefit that can be obtained will, however, not only depend on C storage in the ecosystem but also on how the harvested biomass is used (Litton, Raich, & Ryan, 2007). In a long-time perspective, the potential C substitution effect, that is, how the biomass produced is used in society, can in fact be the most important factor to consider (Lundmark et al., 2014). Since analysis of standing biomass alone could be misleading, estimates of forestry's climate change mitigation potential should be based on proper life cycle assessments, a task that unfortunately goes beyond the scope of this paper.

#### 4.4 | Trade-offs between ecosystem services and management synergies

The basic rationale of this study was to explore silvicultural practices that have the potential to diversify the use of boreal forests and thus be a way of optimizing provisioning of ecosystem services. In accordance with studies examining the trade-offs between different management options, for instance C cycling and forest structural complexity (Bradford & D'Amato, 2012) or C storage and plant species richness (Burton et al., 2013), we found trade-offs among different ecosystem services and outputs, suggesting that simultaneous enhancement of all outputs is not easily achieved (Table 2). Under such circumstances it is important to understand how the practices influence the delivery of individual services (Bennett et al., 2009), so that appropriate management objectives can be set and best practice to achieve these can be determined. However, given the divergent effects of the different practices observed in our study, it seems

**TABLE 2** Trade-offs among different ecosystem services provided by trees and ground vegetation under five silvicultural practices: Thinning (Th), No thinning (NoTh), N fertilization (N), Thinning + N fertilization (Th+N) and Thinning + N and P fertilization (Th+N+P). Data presented are significant changes in model estimates (planned contrasts, Tukey's HSD  $p < .05$ ) relative to thinning that is the conventional silvicultural practice

Thinning (Th) vs.	Non-timber forest products			Biodiversity		Carbon storage	Timber production
	Lingonberry	Bilberry	Lichens	Shannon's <i>H</i>	Species richness	Standing biomass	Stem volume increment
No thinning (NoTh)	ns	ns	-80	-10	-12	+11	+16
N fertilized	-64	ns	-100	-28	ns	+84	+48
Th+N	ns	ns	-59	-11	ns	ns	+28
Th+N+P	-26	ns	-66	-9	ns	ns	+29

Values are expressed in percentage.

plausible that a combination of practices may be used to moderate some negative effects on one output, while retaining the positive effects on another. For example, the lower production potential of lingonberry in N fertilized forests was essentially absent when fertilization was combined with thinning. However, as the overall results suggest that thinning promotes many of the alternative values of forests, but reduce forest biomass production, it seems unlikely that non-timber ecosystem outputs can be promoted without at least some reduction in forest biomass production.

An important caveat when it comes to diversity responses is that our analyses are limited to the responses of the ground vegetation. Other components of the forest biota, for example, saproxylic species that depend on long continuity and high diversity of dead wood, may respond very differently. This implies that the trade-off between values promoted by forestry and those impeded by it may be greater than our study indicates, especially if pristine forest, or forest with limited impact from previous forestry is considered. Accordingly, the effects of thinning will under such circumstances be different than our results indicate.

## 5 | CONCLUSIONS

Our study highlights that forestry influences the multi-use potential of forest ecosystems, but also that there were clear trade-offs among values. Nevertheless, our study shows that the delivery of ecosystem services can be determined by the choice of management. We conclude that, with appropriate management objectives, traditional silvicultural practices can be used to adjust, maintain or even increase the multi-use potential of boreal forests. The first steps towards frameworks that optimize trade-offs between different objectives have already been suggested (e.g. Bradford & D'Amato, 2012). However, to be successful, such frameworks not only require input data on how relevant values are influenced by different silvicultural practices, as provided by our study, but also addressing whether all values should be provided everywhere, or if the provisioning of certain values should be spatially separated. In the case when there are trade-offs among the delivery of values, the latter may be more efficient than trying to develop practices that optimize multi-use delivery everywhere. In this context, the "ecosystem service bundle

approach" suggested by Raudsepp-Hearne, Peterson, and Bennett (2010), is a promising approach for developing landscape level management strategies. This approach suggests grouping values that are positively correlated into bundles, and adjusting the management to maximize the delivery of the values represented by the bundle. In our case, production potential of lingonberry and timber can represent such a bundle, as thinning combined with fertilization promoted timber production without negative effects on berry production. However, if there are strong trade-offs among values, as in our case between potential for reindeer grazing and carbon storage, management with a single-value approach, that shifts targeted values across the landscape, would likely be a more efficient strategy.

An important obstacle for developing multi-use management schemes is that while society in Sweden, and elsewhere, commonly advocates further development of the forests' multi-use potential, the incentives for forest owners to increase the production of non-commercial ecosystem services at the expense of commercial ones may be rather limited. However, if such obstacles are overcome, managing forests from a multi-use perspective can be an efficient and better way to take advantage of the vast possibilities that the circumpolar boreal forest biome offers.

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## AUTHORS' CONTRIBUTIONS

J.S. and A.N. conceived the ideas; E.P.A. and T.L. compiled data, E.P.A. analysed the data; J.S. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.



## DATA ACCESSIBILITY

Data available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.d5m8f> (Strengbom, Axelsson, Lundmark, & Nordin, 2017).

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## SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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Table S1. Descriptive information of the 27 experimental sites included in the experiment at the time of vegetation sampling (2009 or 2010).

Site number	Latitude (N)	Treatment initiation (yr)	Last thinning (yr)	Total N applied (kg N ha <sup>-1</sup> )	Tree age (yr)	Mean top tree height (m)
787	60.79	1973	1997	1050	69	26.7
895	60.28	1970	2007	1050	73	24.8
900	58.35	1966	1999	1050	78	26.3
902	60.01	1969	1989	1050	77	24.9
910	57.34	1966	1988	1200	80	25.0
912	57.8	1969	1995	1050	80	21.5
918	60.65	1970	2000	1050	86	23.5
922	57.89	1967	2007	1200	88	25.6
923	57.85	1973	1997	1050	76	23.7
926	64.39	1969	1996	700	88	23.9
927	65.15	1969	1993	700	84	23.9
929	59.17	1970	1998	1050	83	25.2
931	57.56	1973	1995	1050	74	24.5
933	59.12	1973	2003	1050	90	21.3
935	61.92	1971	2007	700	74	23.4
936	61.87	1974	1998	700	70	24.0
940	56.39	1966	1996	1200	87	24.8
945	63.47	1973	2001	700	57	22.9
947	64.51	1978	1996	600	66	22.3
951	66.95	1975	2005	600	82	19.9
952	66.72	1975	2002	600	87	21.1
992	65.89	1980	2004	600	74	19.3
994	67.48	1978	2006	600	81	17.8
1000	65.84	1981	2000	600	63	21.3
1005	63.83	1980	1996	600	65	24.2
1007	63.62	1977	1997	600	70	22.1
1009	63.62	1981	1999	600	64	20.7

Table S2. List of species recorded in the five different forest types. Treatments were Unthinned stands (NoTh), nitrogen fertilized stands (N), thinned stands (Th), stands both thinned and nitrogen fertilized (Th+N), and stands thinned and fertilized with both nitrogen and phosphorous.

<b>Species</b>	<b>NoTh</b>	<b>N</b>	<b>Th</b>	<b>Th+N</b>	<b>Th+N+P</b>
<i>Vaccinium myrtillus</i>	1	1	1	1	1
<i>Vaccinium vitis-idaea</i>	1	1	1	1	1
<i>Vaccinium uliginosum</i>	1	0	1	1	1
<i>Calluna vulgaris</i>	1	1	1	1	1
<i>Ledum palustre</i>	0	0	1	1	1
<i>Arctostaphylos uva-ursi</i>	0	0	1	0	1
<i>Empetrum nigrum</i>	1	1	1	1	1
<i>Pteridium aquilinum</i>	1	1	1	1	1
<i>Dryopteris carthusiana</i>	0	0	0	1	1
<i>Dryopteris expansa</i>	0	1	0	0	0
<i>Gymnocarpium dryopteris</i>	0	1	0	1	1
<i>Lycopodium annotinum</i>	1	0	1	1	1
<i>Diphasiastrum complanatum</i>	0	0	1	1	0
<i>Anemone nemorosa</i>	0	0	1	1	0
<i>Rubus saxatilis</i>	1	0	1	1	0
<i>Rubus idaeus</i>	0	1	0	1	1
<i>Potentilla erecta</i>	0	0	1	0	0
<i>Oxalis acetosella</i>	1	1	0	1	1
<i>Geranium sylvaticum</i>	0	1	0	0	1
<i>Epilobium angustifolium</i>	1	1	1	1	1
<i>Trientalis europaea</i>	1	1	1	1	1
<i>Galium uliginosum</i>	0	0	0	0	1
<i>Galium saxatile</i>	0	1	0	0	0
<i>Veronica officinalis</i>	0	0	0	1	0
<i>Melanpyrum pratense</i>	1	1	1	1	1
<i>Linnaea borealis</i>	1	1	1	1	1
<i>Solidago virgaurea</i>	1	1	1	1	1
<i>Maianthemum bifolium</i>	1	1	1	1	1
<i>Convallaria majalis</i>	0	1	0	0	0
<i>Luzula pilosa</i>	1	1	1	1	1
<i>Deschampsia flexuosa</i>	1	1	1	1	1
<i>Deschampsia cespitosa</i>	0	1	0	0	1
<i>Agrostis capillaris</i>	0	0	0	0	1
<i>Calamagrostis arundinacea</i>	1	1	1	1	1
<i>Milium effusum</i>	0	0	0	1	1
<i>Carex globularis</i>	0	0	0	1	0
<i>Carex</i> spp	0	0	0	1	1
<i>Sphagnum girgensohnii</i>	0	0	0	1	1
<i>Andrea rupestris</i>	0	0	0	1	0
<i>Polytrichum commune</i>	1	1	1	1	1

Polytrichum strictum	0	0	0	1	1
Polytrichum juniperinum	1	1	1	1	1
Dicranum polysetum	1	1	1	1	1
Dicranum scoparium	1	1	1	1	1
Dicranum majus	1	0	1	0	1
Dicranum spurium	0	0	1	0	0
Dicranum fuscescens	1	1	1	1	1
Dicranum flexicaule	1	1	0	0	0
Dicranum drummondii	0	0	0	0	1
Dicranum montanum	0	0	0	1	1
Racomitrium heterostichum	0	0	0	1	0
Racomitrium microcarpon	0	0	1	0	1
Racomitrium spp	1	0	0	0	0
Pohlia nutans	1	0	1	1	0
Pohlia lescuriana	0	0	0	1	0
Pohlia spp	1	0	1	1	1
Rhodobryum roseum	0	1	0	0	0
Plagiomnium affine	0	0	0	1	1
Aulacomnium palustre	1	0	1	1	1
Cirriphyllum piliferum	1	0	0	0	1
Oxyrrhynchium hians	0	0	1	1	0
Plagiothecium denticulatum	1	1	1	1	1
Plagiothecium laetum	0	0	0	1	0
Plagiothecium curvifolium	0	0	0	1	0
Plagiothecium spp	0	0	0	1	1
Hypnum cupressiforme	0	0	0	0	1
Ptilium crista-castrensis	1	1	1	1	1
Rhytidiadelphus squarrosus	0	0	0	1	1
Rhytidiadelphus triquetrus	0	1	1	1	0
Pleurozium schreberi	1	1	1	1	1
Hylocomium splendens	1	1	1	1	1
Brachythecium spp/Sciuro-hypnum spp	1	1	1	1	1
Warnstorfia spp	0	0	0	1	0
Barbilophozia lycopodioides	0	1	0	0	1
Jungermannia spp	1	0	0	0	0
Lophocolea bidentata	0	0	0	1	0
Lophocolea heterophylla	0	1	0	0	0
Ptilidium ciliare	1	0	1	1	1
Ptilium pulcherrimum	0	0	1	0	0
Cetraria islandica	1	0	1	1	1
Cladonia rangiferina	1	1	1	1	1
Cladonia arbuscula	1	1	1	1	1
Cladonia digitata	0	0	1	0	0
Cladonia gracilis	1	0	1	0	0
Cladonia pleurota	0	0	1	0	0
Cladonia cornuta	1	0	1	0	1

<i>Cladonia crispata</i>	1	0	1	1	0
<i>Cladonia bellidiflora</i>	0	0	1	0	0
<i>Cladonia pyxidata</i>	0	0	1	0	0
<i>Stereocaulon paschale</i>	0	0	1	0	0
<i>Peltigera aphthosa</i>	0	0	1	0	0

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