GCB-BIOENERGY
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY · Open Access

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Effects of whole-tree harvesting at thinning and subsequent compensatory nutrient additions on carbon sequestration and soil acidification in a boreal forest

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Abstract

Residues from forest harvesting operations may be utilized as a renewable energy source. However, the sustainability of this practice has been questioned due to the losses of nutrients and exchangeable base cations, which may impair the forest's carbon sequestration capacity and lead to soil acidification. We report the 18 year response of biomass growth, soil carbon stock and soil chemistry to whole-tree harvest at thinning and associated compensatory measures in a *Pinus sylvestris* forest in northern Sweden. The whole-tree harvest at thinning was combined with nutrient additions to compensate for the nutrient loss caused by extracting the residues. Four main treatments, stem-only thinning, whole-tree thinning, whole-tree thinning with one-time nitrogen fertilization and whole-tree thinning with repeated nitrogen fertilization every third year were applied, with plots split for wood-ash treatment. Eighteen years after the treatments, whole-tree thinning that had removed 3.0 ± 0.2 Mg C/ha in residues had no effect on forest growth, soil carbon and nitrogen stocks or soil chemistry. Both nitrogen fertilization regimes increased biomass growth, but neither one resulted in a significant increase in soil carbon stock. Wood-ash addition increased soil pH and exchangeable base cations, but did not affect carbon stock in biomass or soil. Our long-term data suggest that utilizing harvesting residues for biofuel feedstocks is appropriate in this type of forest. Hence, any nitrogen and wood-ash additions appear unnecessary as compensatory measures for the removal of harvesting residues, but nitrogen can be applied to increase forest growth following thinning.

KEYWORDS
bioenergy crop, fertilization, logging residue, net primary production, *Pinus sylvestris*, soil acidification, whole-tree harvesting, wood ash

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1 | INTRODUCTION

Bioenergy can play a key role in achieving the EU's renewable energy targets for 2030 and beyond (European Union, 2019). In Sweden and other member states of the EU, bioenergy represents a growing share of renewable energy, most of which comes from forest biomass in the form of direct supplies (e.g. harvesting residues) and indirect supplies (e.g. by-products from industry). The use of harvesting residues (slash) from final fellings and thinnings for energy production, that is, whole-tree harvesting, has become an established practice in Sweden and other European countries (de Jong, Akselsson, Egnell, Löfgrend, & Olsson, 2017; Repo et al., 2012; Routa, Kellomäki, Kilpeläinen, Peltola, & Strandman, 2011; Routa et al., 2013). Each year in Sweden, the practice is now carried out on ~25% of the total area subjected to clear-cutting and thinning, and it has been considered possible that it could increase up to 50% of the area (Börjesson, Athanassiadis, Lundmark, & Ahlgren, 2015; de Jong et al., 2017; Swedish Forestry Agency, 2014).

The sustainability of whole-tree harvesting has been questioned because nutrient concentrations in harvesting residues are high, and thus the export of nutrients via whole-tree harvesting is markedly increased. Decline in site productivity and increased soil acidification following whole-tree harvesting has therefore been expected and frequently demonstrated in field experiments (Kimmins, 1976; Löfgren, Ågren, Gustafsson, Olsson, & Zetterberg, 2017; Olsson, Bengtsson, & Lundkvist, 1996; Thiffault et al., 2011; Walmsley, Jones, Reynolds, Price, & Healey, 2009). In particular, loss of nitrogen is of great concern in boreal forests because forest production in these regions is strongly nitrogen limited (Lim et al., 2017; Tamm, 1991; Werhahn-Mees, Palosuo, Garcia-Gonzalo, Röser, & Lindner, 2010).

Two measures have been recommended to compensate for the nutrient losses associated with whole-tree harvesting—nitrogen fertilization and wood-ash addition. Nitrogen fertilization alleviates the general nitrogen limitation to tree growth that may be amplified by extracting harvesting residues. The primary rationale for the application of wood-ash, which contains almost no nitrogen, is to compensate for the loss of base cations and to counteract soil acidification (Swedish Forest Agency, 2008, 2019a, 2019b). Wood-ash applications have commonly no effect on forest growth, except for applications to drained peatland soils where tree growth is often limited by potassium and phosphorus, the relatively abundant elements in wood-ash (Huotari, Tillman-Sutela, Moilanen, & Laiho, 2015). In boreal forests, wood-ash applications can sometimes have negative effects on tree growth, and hence application of both nitrogen and wood-ash has been recommended (Jacobson, Lundström, Nordlund, Sikström, & Pettersson, 2014).

However, to our knowledge, no field study has examined the effects of nitrogen fertilization and wood-ash addition in a factorial way following whole-tree harvesting at thinning, and only a few field-based studies have combined whole-tree harvesting with nutrient compensation treatments (e.g. Helmisaari et al., 2011; Sherman, Dumroese, & Coleman, 2018; Tveite & Hanssen, 2013). Moreover, reported studies often neglected a holistic assessment of both above- and below-ground responses, hindering the ability to propose strategies for sustainable forest management.

The aim of this study was to examine long-term effects of whole-tree thinning on carbon sequestration capacity and soil chemistry in a forest ecosystem, and to assess the effects of compensatory measures that appear in management recommendations. We examined the combined effects of whole-tree thinning with two nitrogen fertilization treatments (single application to compensate for lost nitrogen, or repeated application every third year), and used a split-plot design to analyse the effects of wood-ash addition. This experimental setting allowed the assessment of the interaction between nitrogen and other nutrient demands under the ambient and the treatment conditions.

We hypothesized that whole-tree thinning causes reductions in biomass and soil carbon stocks, and soil acidification, compared to stem-only thinning, and those reductions can be amended by additions of nitrogen and wood-ash. To test the hypothesis, we formulated five predictions:

1. Whole-tree thinning reduces tree growth and soil carbon stock build-up compared to stem-only thinning;
2. a single application of nitrogen fertilizer compensates for these reductions;
3. repeated nitrogen fertilization results in sustained and increased tree growth and higher build-up of soil carbon;
4. wood-ash application amplifies the effect of repeated nitrogen fertilization on biomass growth; and
5. wood-ash application increases soil pH and exchangeable base cation contents in the soil.

2 | MATERIALS AND METHODS

2.1 | Study site

In 2001, the study was first designed in a 35-year-old *Pinus sylvestris* forest in Rödålund (64.14°N, 19.85°E, 209 m a.s.l.), near Vindeln, Västerbotten county, Sweden, a common type of forest stands in the managed forests of these regions (Figure S1). The forest is located along the Vindeln River, on generally flat land (maximum slope of 5°). The soil texture is sand, Albic Podzol with a mor organic layer ranging in thickness from 2 to 5 cm. The site was planted with *P. sylvestris* seedlings in 1966, and later subdominant species,

Picea abies (18%) and *Betula* spp. (8%), regenerated. The area is generally covered by snow from late October to early May. The understorey vegetation is dominated by dwarf shrubs, *Vaccinium myrtillus* (bilberry) and *Vaccinium vitis-idaea* (lingonberry), a ground layer of mosses, *Pleurozium schreberi* and *Hylocomium splendens* and lichens, *Cladonia* spp. The mean annual temperature is 2.3°C, measured at the Svartberget field station ~10 km from the study site (1991–2018). Mean annual rainfall is ~600 mm, of which a third falls as snow, covering the frozen ground from mid-October to early May. The length of the growing season (the period with a daily mean air temperature ≥ 5°C) averages ~150 days from May to September (Ottosson Löfvenius, 2019).

2.2 | Experimental design

In June 2001, 24 plots (60 × 70 m^2) were established. Average stand density across plots was 2037 ± 48 trees ha^{-1}, basal area 19.4 ± 0.6 m^2/ha and standing stem volume over bark 118.0 ± 3.7 m^3/ha (mean ± *SE*, n = 24; Table 1) with an annual stem increment of ~8 m^3 ha^{-1} year^{-1}. The six blocks were identified based on standing basal area, and the four treatments were randomly assigned within each block. The main treatments were stem-only thinning; whole-tree

thinning; whole-tree thinning with a compensatory nitrogen fertilization; and whole-tree thinning with repeated nitrogen fertilization every third year. A wood-ash treatment was applied across all treatments in a split-plot design. Each plot was split into two equal subplots, and wood-ash was randomly assigned to one of the subplots.

In October 2001, the thinning operation commenced, targeting 30% basal area removal. The amounts of carbon and nitrogen in harvesting residues left on the plots with stem-only thinning were 2.7 ± 0.3 Mg C/ha and 33.8 ± 3.4 kg N/ha. The extracted amounts of carbon and nitrogen in harvested branches and needles in the whole-tree thinning treatment were 3.0 ± 0.2 Mg C/ha and 37.8 ± 2.9 kg N/ha (Table 1). After thinning, the fertilization treatments started in June 2002 using a commercial fertilizer for forests (Skog-CAN; Yara), of which the substance contains NH$_4$ (13.5%), NO$_3$ (13.5%), Ca (5%), Mg (2.4%), B (0.2%). The level of the compensatory fertilization was set to 150 kg N/ha, the most common dose in practical forestry for its cost-effectiveness (Table 2). In the repeated fertilization plots, 150 kg N/ha was added in June 2002, 2005, 2008, 2011, 2014 and 2019. Tree measurements in 2019 were made in June, and thus, did not capture the 2019 fertilization effect. Therefore, the total amount of the repeated fertilization was 750 kg N/ha at the time of the current study. In 2005, hardened-crushed

TABLE 1 Description of study plots and thinning intensity (mean ± SE, n = 6)

	Stem-only thinning	Whole-tree thinning	Whole-tree thinning + one-time fertilization	Whole-tree thinning + repeated fertilization
Initial conditions				
Stand density (trees ha^{-1})	1,963 ± 110	2,108 ± 91	2,025 ± 30	2,040 ± 151
Stem volume (m^3/ha)	86.3 ± 7.5	94.2 ± 8.5	89.9 ± 9.9	86.0 ± 7.8
Basal area (m^2/ha)	18.6 ± 1.1	20.4 ± 1.3	19.5 ± 1.1	19.1 ± 1.3
Thinning-associated removals				
Stand density (trees ha^{-1})	707 ± 85	825 ± 52	710 ± 51	818 ± 127
Basal area (m^2/ha)	5.5 ± 0.4	6.8 ± 1.1	5.8 ± 0.5	5.9 ± 0.6
Stem volume (m^3/ha)	24.6 ± 2.6	32.2 ± 6.1	25.6 ± 4.1	25.4 ± 2.9
Branches (Mg C/ha)	1.42 ± 0.13	1.71 ± 0.30	1.58 ± 0.18	1.60 ± 0.16
Foliage (Mg C/ha)	1.25 ± 0.16	1.53 ± 0.22	1.22 ± 0.18	1.34 ± 0.17
Carbon stock in the residues (Mg C/ha)	2.66 ± 0.27	3.25 ± 0.52	2.80 ± 0.35	2.93 ± 0.31
Branches (kg N/ha)	12.30 ± 1.12	14.89 ± 2.60	13.73 ± 1.57	13.86 ± 1.43
Foliage (kg N/ha)	21.53 ± 2.43	26.84 ± 4.18	21.42 ± 3.01	22.67 ± 2.49
Nitrogen stock in the residues (kg N/ha)	33.83 ± 3.38	41.73 ± 6.75	35.15 ± 4.53	36.54 ± 3.69
Removals from the thinning in 2013				
Stand density (trees ha^{-1})	261 ± 18	289 ± 20	300 ± 22	258 ± 12
Basal area (m^2/ha)	3.9 ± 0.3	3.9 ± 0.3	4.5 ± 0.3	5.2 ± 0.3
Stem volume (m^3/ha)	28.4 ± 2.5	26.8 ± 2.4	32.1 ± 2.4	38.1 ± 2.1

TABLE 2 Nutrient contents of the fertilizer (Skog-Can; kg/ha per dose) and wood-ash (kg/ha)

Treatment	N	P	Ca	Mg	K	Na	B	S
Nitrogen fertilizer	150		28	13			1	
Wood-ash		48	420	51	189	19	1	103

wood-ash (3 Mg/ha) was added in the ash-split plots (Table 2). The origin of the wood-ash was 50% slash, 50% shavings, bark and chips. The ash was fly-ash obtained from a boiler with a bubbling fluidizing bed with flue gas condensation produced at Falun district heating plant in 2003–2004. In November 2013, all plots were subjected to an additional stem-only thinning with an equal intensity across the treatments (Table 1; $-23.4 \pm 0.6\%$, -277 ± 9 trees ha^{-1}; $p = .684$ for stand density difference between treatments). Although this thinning was an accidental operation from the experimental design, it did not introduce a bias to the design, and the post-thinning response was included in our analyses.

2.3 | Estimation of standing biomass

We estimated standing and thinned biomass based on a combination of allometric equations and repeated measurements of the trees' dimensions. Destructive harvesting was performed twice, first during the initial thinning treatments and then 6 years after the treatment commenced (October 2001 and October 2008). This allowed us to capture changes in tree allometries. Stem diameter at 1.3 m of all trees and height of 20 sample trees in each plot were measured in June 2001, April 2002, March 2005, October 2009, October 2013 and June 2019. Measurements made before the growing season (May–September) were considered to represent growth during the previous year. Tree dimensions in 2019 were measured in the middle of the growing period. Therefore, the duration of the period of growth between 2013 and 2019 was set to 5.5 years. Based on relationships between stem diameter at 1.3 m and tree height, following the recommendation of Näslund (1947), parameters of the function were estimated in each year for each plot, and then applied to each individual tree.

In the first destructive biomass sampling, we selected 20 *P. sylvestris* and 10 *P. abies* trees. Trees were cut at ~0.2 m above ground level. After felling, we recorded stem length and stem diameter at every metre, including at 1.3 m. Length of the live crown was divided into four equal strata. In each crown stratum, two representative branches including foliage, twigs, cones and dead branches were fresh-weighed in the field. The remaining fresh branches were weighed in the field separately for each stratum. Stem disks (~5 cm thickness) were taken at 0, 1.3 m and at 30%, 55%, 70% and 85% of the stem length, and weighed in the field. Collected samples were then stored in the freezer for further analyses.

In the laboratory, samples were dried at 65°C to constant weight, and separated into each component, stem wood and bark from disk samples, and foliage, twigs, cones and dead twigs from the sample branches. A dry to fresh mass ratio was then applied to field-measured fresh mass for each component to estimate its biomass. Based on the component biomass, we developed allometric functions to estimate stem volume, and above-ground carbon and nitrogen stocks. Stem diameter at 1.3 m and tree length were used as independent variables to predict stem volume, and biomass of stem wood, stem bark and branches; and a single variable, stem diameter at 1.3 m, represented foliage. Allometric functions were affected by neither treatment nor year, and thus the functions were based on data pooled across treatments and years. Employing the allometric functions to stem diameter at 1.3 m and modelled tree height of individual trees in the plots, we estimated stem volume and each component of above-ground biomass. Biomass of coarse-roots (≥ 2 mm) for *P. sylvestris* and *P. abies*, and biomass of *Betula* spp. were estimated using national functions (Marklund, 1988; Petersson & Ståhl, 2006). Carbon and nitrogen stocks in biomass were calculated by multiplication of biomass, and carbon and nitrogen concentrations for individual trees and biomass components. Amounts of stem volume, and carbon and nitrogen stocks at the plot scale were calculated as the sum of individual trees in each plot. Carbon and nitrogen concentrations in above-ground tree components (i.e. needles, branches, stem wood and stem bark) were determined by a dry oxidation method using ball-milled subsamples (Flash EA 2000; Thermo Fisher Scientific). Carbon and nitrogen concentrations in coarse-root biomass were assumed to be the same as in stem wood.

2.4 | Estimation of soil carbon and nitrogen stocks, and soil chemistry

In the autumn 2017, 12 soil cores were sampled from each of the split plots, and divided into organic (humus) and mineral soil layers (0–5, 5–10, 10–15 and 15–20 cm), and the samples from each layer were pooled plot-wise. The organic layer was sampled using a 10 cm diameter corer, and the mineral soil was sampled using a 3 cm diameter corer. Humus samples were sieved through a 5 mm steel mesh and the mineral soil was sieved through a 2 mm steel mesh. Samples were then dried at 85°C to constant weight. The mass of the organic layer (kg/m^2) was estimated by dry mass divided by the cross-sectional area of the sampling corer (78.5 cm^2). The mass of the mineral soil was estimated by the following equation:

$$M_M = BD \cdot \text{sampling depth} \cdot (1 - S), \tag{1}$$

where M_M is the mineral soil mass (kg/m^2), BD is bulk density (kg/m^3) of the fine soil (<2 mm) and S is the stoniness, that is, the volume fraction of stones (>20 mm). Stoniness was estimated using the penetration method according to Stendahl, Lundin, and Nilsson (2009), by measuring depth penetration with a 1 cm thick steel rod pressed down to the deepest depth in the mineral soil up till 30 cm. Measurements of stoniness were made at 25 locations per plot, in a total of 10 plots distributed all over the study site. Because the soil sampling method did not allow estimation of representative bulk density, BD was calculated from the pedotransfer function (Equation 2; Nilsson & Lundin, 2006),

$$BD = 1546.3 \cdot e^{-0.313 \cdot C^{0.5}} + 0.00207 \cdot l, \quad (2)$$

where C is the carbon concentration (%) of the pooled sample and l is the mean depth (cm) for each soil layer.

The total carbon and nitrogen concentrations in soil samples were determined by the same method as for the biomass samples described above. Exchangeable base cations (Na$^+$, K$^+$, Ca^{2+}, Mg^{2+}, Al^{n+}) were determined by extraction in 1 M NH$_4$Cl followed by determination of the element content in the filtered extract with ICP. Soil pH$_{(H_2O)}$ was determined using standard methods with a glass electrode and soil-to-water ratio of 1:5. Soil mass per unit area (hectare) for each layer was calculated based on the depth of the layer and the estimated bulk density. Total stocks of carbon and nitrogen in the soil were calculated by multiplying the element concentration by the soil layer mass.

2.5 | Statistical analysis

The effects of the main treatments and the split-plot treatment (wood-ash) on above- and below-ground variables were determined using a mixed effect ANOVA to account for the randomized complete block with split-plot design.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} + \gamma_k + (\alpha\gamma)_{ik} + \varepsilon_{ijk}, \quad (3)$$

where Y_{ijk} is the response variable in the jth block with the main treatment i and split wood-ash treatment k. μ is the grand population mean, α is the fixed effect of the main treatment, β is the random effect of block, γ is the fixed effect of the wood-ash treatment and $\alpha\gamma$ is the corresponding interaction term. ε_{ij} is the whole-plot error associated with interaction between block and the main treatment, ε_{ijk} is the split-plot error (the final residuals). Variables of trees were separately analysed for each year and soil for each depth.

Statistical analyses were performed using R (v. 3.2.2): the *nls* function was used to estimate parameters for the Näslund function; the *lm* function was used for devising allometric equations; and the *lme* function in the nlme package was used

to examine the mixed effect ANOVA model (Equation 3). To compare and separate means, Tukey's test with $p = .05$ was employed using *lsmeans* and *cld* functions in the lsmeans package. The final residuals (ε_{ijk}) were normally distributed, determined by plotting the final residuals against predictions.

3 | RESULTS

3.1 | Stem volume, and biomass carbon and nitrogen stocks

Whole-tree thinning did not reduce biomass growth over 18 years in comparison with the stem-only thinning (minimum $p = .562$ for the growth between 2003 and 2019; Table S1), resulting in no difference in biomass stocks between the two treatments ($p = .996$; Figure 1). Both nitrogen fertilization treatments enhanced production (Figure 1b,d,f). The one-time nitrogen fertilization increased biomass production, yielding an extra biomass of 3.3 ± 0.7 Mg C/ha
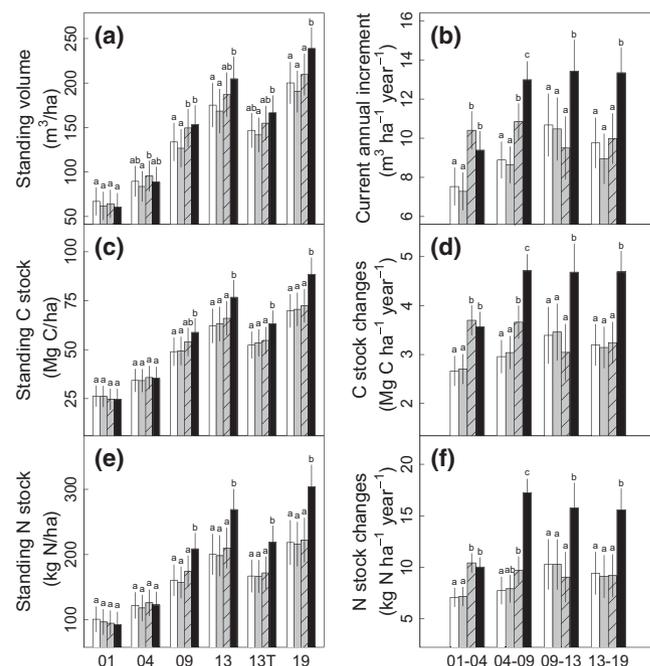
FIGURE 1 (a, c, e) Standing volume, carbon (C), and nitrogen (N) stocks in total biomass and (b, d, f) associated stock changes. Wood-ash addition affected none of these quantities, and therefore data were pooled across the ash addition treatments in the analysis (Table S1). The first thinning was undertaken in October 2001 and the second in November 2013. In the second thinning, all plots were stem-only thinned. Numbers on the x-axis are the years starting in 2001 and 13T indicates the measurements taken after the second thinning in 2013. Different letters indicate significant differences between treatments within year ($p < .05$). Error bars represent a 95% confidence interval. Open bar: stem-only thinning, grey bar: whole-tree thinning, hatched grey: whole-tree thinning + one-time fertilization, black bar: whole-tree thinning + repeated fertilization
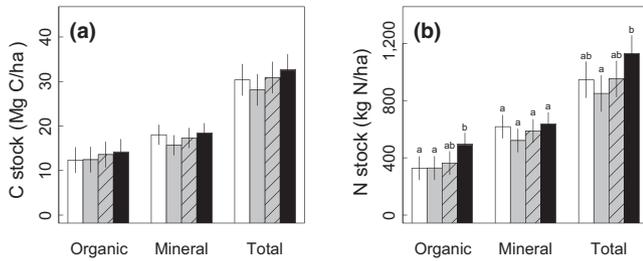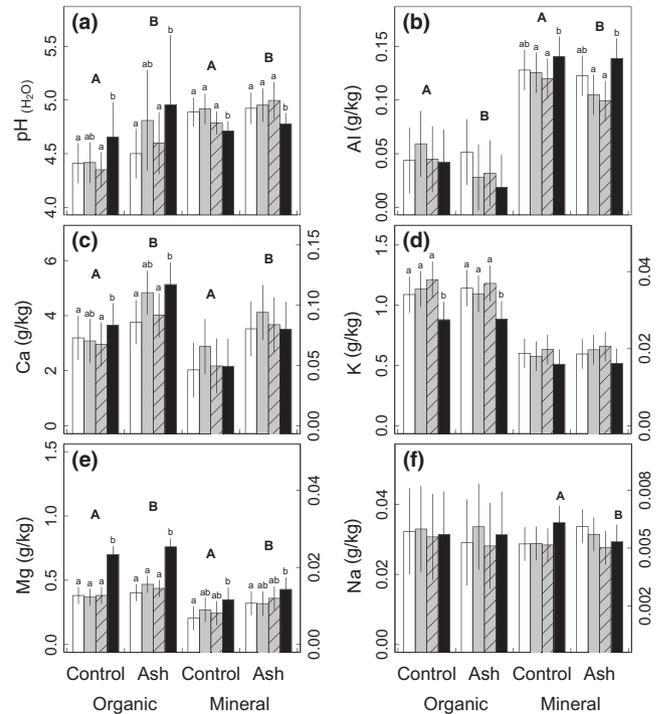
FIGURE 2 (a) Soil carbon (C) and (b) nitrogen (N) stocks in the organic and mineral soils (0–20 cm depth). Open bar: stem-only thinning, grey bar: whole-tree thinning, hatched grey: whole-tree thinning + one-time fertilization, black bar: whole-tree thinning + repeated fertilization. Wood-ash addition affected none of these quantities and therefore data were pooled across the ash addition treatments in the analysis (Table S1). Error bars represent a 95% confidence interval. Different letters indicate significant differences between treatments within year (p < .05)

(mean $\pm$ SE; p = .003; 16.8 $\pm$ 2.9 m^3/ha in volume). The repeated fertilization sustained the enhanced growth rate at an average of 46.1 $\pm$ 8.5% over the 18 years, leading to a greater stock accumulation with extra biomass amounting to 19.4 $\pm$ 3.5 Mg C/ha (p < .001; 49.9 $\pm$ 9.9 m^3/ha in volume). Wood-ash addition did affect neither stem volume nor biomass stocks, regardless of the main treatments (minimum p = .061 for annual volume increment between 2013 and 2019; Table S1).

Whole-tree thinning did not affect soil carbon or nitrogen stock (Figure 2; minimum p = .121 for nitrogen in the mineral layer), or soil chemistry compared to stem-only thinning (Figure 3; minimum p = .311 for Ca concentration in the mineral layer). Whole-tree thinning + repeated fertilization significantly increased nitrogen stock in the organic layer (60 $\pm$ 18%, p = .008) but not in the mineral soil (23 $\pm$ 8%, p = .058; Figure 2). Neither fertilization regime affected soil carbon stock (p = .144).

The wood-ash treatment increased soil pH in the organic layer and in the upper mineral soil at 0–10 cm, but not in deeper layers (Figure 3; Table S2). There was no interaction between the main treatments and wood-ash treatment for soil pH (p = .407). The repeated fertilization increased pH in the organic layer (p = .010) but decreased in the mineral soil compared to the other main treatments (p = .004).

Exchangeable Al decreased in the soil as an effect of replacement with added base cations on exchange sites (Figure 3; Table S2 and p values therein). Wood-ash addition increased exchangeable soil Ca stocks and to a lesser extent Mg stocks. As the applied fertilizer also contains the same amount of Mg as the applied wood-ash, the largest concentrations and stocks of Mg were observed in the plots with a combination of the repeated fertilization and wood-ash (Table S3). Exchangeable Na and K were responsive to the repeated fertilization in both the organic and mineral soil layers, but the change was less than the response of Ca.


FIGURE 3 (a) pH and (b–f) concentration of exchangeable cations (Al, Ca, K, Mg, and Na) in the organic and mineral soils (0–20 cm depth) in combinations of wood-ash addition and the main treatments. Ash treatment (uppercase letters) and repeated fertilization (lowercase letters) affected measures of soil chemistry, whereas whole-tree thinning did not affect any of soil chemistry measures. Open bar: stem-only thinning, grey bar: whole-tree thinning, hatched grey: whole-tree thinning + one-time fertilization, black bar: whole-tree thinning + repeated fertilization. Error bars represent 95% confidence interval. Different lowercase letters indicate differences between the main treatments within wood-ash treatment in each soil layer; different capital letters indicate difference between wood-ash treatments in each soil layer. Note that no interaction was observed between the main treatment and wood-ash treatment, thus data were pooled between wood-ash treatments or the main treatments in each soil layer, with the exception of Na concentration (p = .008 for interaction between the main treatment and wood-ash addition). Bars without letters indicate no difference between or among the treatments. (f) Wood-ash addition lowered Na concentration only with the repeated fertilization. The effects of wood-ash and the main treatments on exchangeable cation concentrations (Table S2) and weighted stocks by bulk density (Table S3) are presented in the Supporting Information

Exchangeable K stocks in the organic layer following the repeated fertilization were significantly lower compared with the other treatments, probably reflecting the higher growth rate of trees and their demand for K.

4 | DISCUSSION

Over two decades, neither forest growth nor soil carbon stock declined in response to the extraction of harvesting
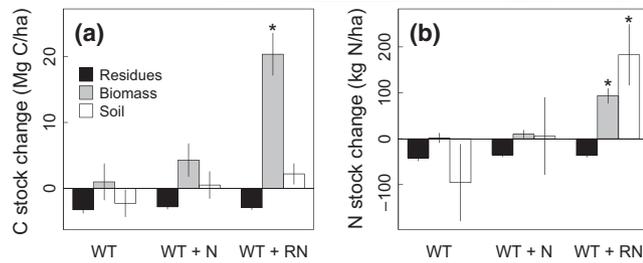
FIGURE 4 (a) Carbon (C) and (b) nitrogen (N) stock change in excess of the stem-only thinning 18 years after the treatment commenced (16 years for soil stocks). Error bars represent a 95% confidence interval. An asterisk indicates that the value differs significantly from 0 ($p < .05$, $n = 6$ blocks). WT, whole-tree thinning, WT + N, whole-tree thinning + one-time fertilization, WT + RN, whole-tree thinning + repeated fertilization

residues at thinning, refuting prediction 1 (Figure 4). The growth response in the last period of growth measurement (2013–2019) might have been influenced by the 2013 stem-only thinning across all plots. However, the amount of residues left on site by the second thinning was clearly inferior to the first thinning treatment (33% of carbon and 17% of nitrogen stocks in the initial treatment), and there was no bias between treatments ($p = .796$ for carbon stock in the residues and $p = .793$ for nitrogen). Effects of the initial treatment could therefore have been slightly masked, but not biased by the second thinning.

The compensatory fertilization increased growth for a short period, whereas the repeated fertilization sustained the increased growth, supporting predictions 2 and 3. Regardless of the fertilization regimes, wood-ash application did not increase biomass production, refuting prediction 4. Taken together, these results indicate that soil nitrogen availability was a major limiting factor to growth of this forest, and increased soil pH and nutrients by the addition of wood-ash had no additive effect on growth.

Despite limitation of nitrogen to tree growth, the extra amounts of nitrogen harvested in the whole-tree thinning treatment (34 kg N/ha) was not of significance for making a change in tree growth. This result from one field experiment should be viewed in the broader picture of meta-analyses of a large number of experiments made across the Nordic countries. These studies show that on average, residue removals at thinning may reduce growth of standing volume by ~5%. The effect was, however, highly variable between stands, and less pronounced in *P. sylvestris* forests than in *P. abies* (Egnell, 2017; Helmisaari et al., 2011; Jacobson, Kukkola, Mälkönen, & Tveite, 2000). The meta-study by Helmisaari et al. (2011) concluded that the growth reduction in *P. sylvestris* stands following whole-tree thinning was greater during the second decade, indicating a long-term response, and that the loss of nutrients, in particular nitrogen, was responsible for the growth reduction. On the other hand, the study

by Egnell (2017), which contained data from Helmisaari et al. (2011), concluded that the growth reduction by whole-tree thinning was not clearly explained by the amounts of the extracted nutrients in the residues, ranging 20–160 kg N/ha, site productivity, or their interactions.

Several processes may explain why simply the extracted amounts of nitrogen failed to explain growth responses. First, the amounts of extracted nutrients in the thinning residues are generally low in comparison to standard nitrogen fertilization doses or amounts of nitrogen removed by whole-tree harvesting at final fellings (Hyvönen, Olsson, Lundkvist, & Staaf, 2000; Walmsley et al., 2009). Second, actual quantity of released nitrogen via decomposition is expected to be low in boreal regions under cold temperatures. Indeed, in similar *P. sylvestris* forests as the current study stand, harvesting residues at final fellings resulted in a net nitrogen mineralization rate of <5 kg N ha^{-1} year^{-1} (Hyvönen et al., 2000), and thus a much lower rate of net nitrogen mineralization is expected from the residues at thinning. Moreover, as pointed out by Egnell (2017), a short-term mulching effect on soil temperature and moisture induced by residues left on the sites may have confounded potential explanatory variables across the stands.

The amount of carbon in residues left on site during the stem-only thinning treatment, 2.7 ± 0.3 Mg C/ha (Table 1), was fairly substantial relative to the carbon stock in the organic layer (21%) and the total carbon stock (~10%), but it nevertheless had no effect on measured carbon stocks in the soil (Figure 4). This result is in line with other observations, namely that expected differences in soil carbon stocks following whole-tree harvest are rarely revealed in field experiments (Olsson et al., 1996; Walmsley et al., 2009; see review by Thiffault et al., 2011). The most likely explanation is that only small quantity of residues became recalcitrant organic matter incorporated in soil organic layer, while most of the carbon in residues may actually have decomposed after a few decades (~80% mass loss within two decades; Repo et al., 2012).

Several reasons for nutrient recycling with wood-ash following whole-tree harvesting have been put forward. Besides concerns for a decline in site productivity, whole-tree harvesting also leads to increased losses of base cations in harvesting residues, thereby increasing the acid load. Indeed, several long-term field experiments have demonstrated that whole-tree harvesting at *final felling* can lower soil pH and stocks of extractable base cations (Brandtberg & Olsson, 2012; Nykvist & Rosén, 1985; Olsson et al., 1996). However, there are fewer and less conclusive studies examining the effect of whole-tree harvest at *thinning* on soil chemistry (e.g. Olsson, 1999). An important aspect in this type of study is the time that is needed for decomposition and release of nutrients from harvesting residues (Zetterberg, Olsson, Löfgren, Hyvönen, & Brandtberg, 2016). In a short-term study (e.g. Olsson, 1999;

5 years), much of the nutrients of the residues may not be released. Another aspect is the treatment dose. The total amount of base cations in the residues was small in the present study: the amount of base cations extracted by harvesting residues at thinning was 7.5, 2.7 and 18.1 kg/ha for Ca, Mg and K, respectively, estimated based on the nitrogen content of the canopy in the present study (Table 1) and a ratio of element-to-nitrogen in the canopy from an adjacent *P. sylvestris* stand (Lim et al., 2015). These limited extra base cations in the residues would hardly be detected in the soil given the design of the experiment.

To put the treatments in another perspective, the base cation content in the residues was also small compared to the load in the ash treatment. Using the same data as above, base cations in the residues amounted to 5.6 (Ca), 7.3 (Mg), 8.2 (K) and 1.3% (Na) of the wood-ash dose. The experimental wood-ash dose thus represented a large overcompensation for the base cations removed in harvested residues. However, the wood-ash dose was not intended simply to compensate for the removals by whole-tree harvesting at thinning, but was based on the highest dose recommended by the Swedish Forest Agency (2008, updated 2019b). Ash applications in Sweden currently take place mostly in southern provinces, where the acid load from both historic acid deposition and forest growth is higher than in the north. It was thus not surprising that the wood-ash treatment had effects on soil chemistry, and that the effects were mostly apparent in the organic layer.

Demands for harvesting residues for biofuel feedstocks are projected to increase following policies that support reduction of CO_2 emissions and fossil fuel phase-out. Although utilizing harvesting residues at thinning has the potential to benefit the development of bio-economies in boreal forests, the sustainability of this practice has been questioned due to the loss of nutrients in the residues (Repo, Böttcher, Kindermann, & Liski, 2015; Werhahn-Mees et al., 2010). Our two decades observation in a boreal *P. sylvestris* forest, however, does not support the concern of reduced forest carbon sequestration or soil acidification following harvesting residue removal at thinning. This was probably due to the lower amounts of extracted carbon and nutrients in the residues at thinning, compared to those at final fellings. We concluded that the risk is low for carbon sequestration and soil nutrients in boreal *P. sylvestris* forests, when utilizing forest harvesting residues at thinning. Hence, compensatory measures for nutrient losses or soil acidification from whole-tree thinning at such conditions may be unnecessary.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

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