Forest Ecology and Management 580 (2025) 122526

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of logging residue on the growth and properties of the humus layer in Scots pine and Norway spruce stands

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ARTICLE INFO

Keywords:
Forest soil
Logging residues
Nutrients
Picea abies
Pinus sylvestris
Tree growth

ABSTRACT

The utilisation of forest-based primary biomass as a source of renewable energy is becoming increasingly prevalent as a means of reducing the reliance on fossil fuels. However, there has been a growing concern about the potential impact of increased organic matter and nutrient removal on long-term forest productivity. The objective of this study was to investigate the impact of logging residue removal on stand productivity and soil C and N levels in Finland. The material was collected from young Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) stands 20–21 years following the final felling, as well as from a pine experiment that was established in conjunction with an intermediate thinning 20 years ago. In the young stands after final felling, the treatments were whole-tree harvesting, stem-only harvesting, and stem-only harvesting with a double amount of logging residues left on the plots. In the middle-aged stand after thinning, the residue levels were 0, 10, 20, and 30 Mg ha^{-1}. In the young spruce stands, the removal of logging residue following the final felling resulted in a negative growth response, but the doubling of logging residue did not result in a further growth increase. In contrast, no treatment effects were observed in the growth of the Scots pine stands, both in the young stands after final felling and in the middle-aged stand after thinning. In the young stands after final felling, the logging residues had no significant impact on the amounts of humus layer C or N. In contrast, the logging residues increased the levels of both C and N in the humus layer of the middle-aged pine stand after thinning. It can be concluded that the removal of nutrients following the harvest of logging residue in final felling and thinning does not indicate significant issues with regard to the availability of nutrients, based on the data on tree growth.

1. Introduction

The utilisation of forest-based primary biomass as a source of renewable energy is becoming increasingly prevalent as a means of reducing the reliance on fossil fuels and achieving the reduction targets in carbon emissions. The utilisation of forest biomass encompasses logging residues, mainly comprising tree tops, branches, bolts excised due to defects, and stumps, in addition to small-diameter trees derived from thinnings. For example, in 2022 in Finland, heating and power plants consumed 6.6 million m^3 of forest chips produced from small-sized trees and large-sized timber, 2.7 million m^3 from logging residues, and 0.3 million m^3 from stumps (Vaahtera et al., 2023).

There has been a growing concern about the potential consequences of extracting logging residues for bioenergy, in comparison to the conventional stem-only harvesting. The early studies already identified increased nutrient removal and soil acidification as potential factors affecting the long-term maintenance of forest productivity (Mälkönen, 1972; Weetman and Webber, 1972). The removal of nutrients is two to four times greater in whole-tree harvesting than in stem-only harvesting, due to the higher nutrient concentration in foliage and branches compared to stemwood (Mälkönen, 1976; Freedman et al., 1981). However, the removal of logging residues was not observed to have such a large impact on soil nutrient levels in thinned stands sampled 3–30 years later (Tamminen et al., 2012). In any case, the potential effects of logging residue removal are likely to manifest gradually, given that retained residues decompose at a relatively slow rate.

Logging residues represent a considerable organic matter and carbon stock (Clarke et al., 2021). In the final fellings of Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) stands in Finland, the quantities of logging residues were estimated to be 20–60 Mg ha^{-1} and

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https://doi.org/10.1016/j.foreco.2025.122526
Received 8 October 2024; Received in revised form 22 January 2025; Accepted 23 January 2025
Available online 1 February 2025

15–30 Mg ha^{-1}, respectively (Hakkila et al., 1998). The corresponding values obtained in the first thinning stands were 16 Mg ha^{-1} and 9 Mg ha^{-1} (Tamminen et al., 2012). Furthermore, the harvesting of logging residues affects both carbon and nitrogen cycling by modifying the composition of soil organic matter and reducing the mineralisation of C and N (Olsson et al., 1996; Smolander et al., 2010, 2013, 2024; Clarke et al., 2021). As observed by Clarke et al. (2015), whole-tree harvesting in boreal forests has not resulted in a notable long-term decline in soil carbon stocks. Instead, the difference is most often observed in the organic layer, in comparison to stem-only harvesting. However, they emphasised the necessity for further experimental studies to be conducted.

Numerous studies have demonstrated that the removal of harvest residue has resulted in a decline in forest productivity, even in sites with high fertility (e.g., Mendham et al., 2014; Rocha et al., 2016). Consequently, whole-tree harvesting of middle-aged Scots pine and Norway spruce stands in the Nordic countries has resulted in a notable decline in tree growth (Jacobson et al., 2000; Helmisaari et al., 2011; Tveite and Hanssen, 2013).

Nitrogen is often the primary nutrient that limits the growth of boreal and temperate forests on mineral soils (Binkley and Högberg, 2016; Högberg et al., 2017). As the release of N from logging residues is not immediate (Palviainen et al., 2004), a time lag may be observed before the effects of nutrient export become apparent (Egnell, 2011; Ranius et al., 2018). However, a more immediate response to whole-tree harvesting in thinning can be expected in comparison to final felling, given that an established stand more quickly responds to changes in nutrient availability (Egnell, 2017). Nonetheless, the quantity of nitrogen removed with logging residues is less in thinning, with the quantities ranging 20–60 kg ha^{-1} in pine stands and 60–130 kg ha^{-1} in spruce stands (Jacobson et al., 2000, Tamminen et al., 2012). In the case of final felling, the quantities of nitrogen removed are in the range of 75–150 kg ha^{-1} and 150–300 kg ha^{-1}, respectively (Hakkila et al., 1998).

The nutrient demand of seedlings is relatively low in comparison to that of trees at the thinning stage (Rolff and Ågren, 1999). Furthermore, the mineralisation of nutrients is high following the final felling. Therefore, the impact of logging residue removal in final felling on tree growth may be postponed, with discernible effects only becoming evident at a later stage as the stand continues to mature. Accordingly, the harvesting of logging residues has been observed to have no, or only slightly negative, impact on seedling growth in the boreal zone during the first five to fifteen year period (Powers et al., 2005; Saarsalmi et al., 2010; Egnell, 2011). However, as the stand develops over time, a reduction in growth may occur following the harvesting of logging residues. This is due to the increasing nutrient requirement of the growing trees, and nutrients have already been released from the remaining residue (Egnell, 2011; Tamminen and Saarsalmi, 2013). In contrast to thinned stands, the situation following final felling is more complex prior to the development of tree seedlings or other vegetation. This is because logging residues increase the risk of N losses via gaseous emissions and, in particular, via leaching (Lindroos et al., 2016, Smolander et al., 2019, Törmänen et al., 2020). Nevertheless, the impact of these losses is likely to be insignificant in comparison to the inputs.

Smolander et al. (2015) examined the impact of varying quantities of logging residues on soil properties and stand growth in two Scots pine and four Norway spruce experiments ten years after the final felling. They observed that the quantity of logging residues had no consistent impact on seedling growth or on the amounts of carbon and nutrients in the soil. Nevertheless, in some spruce experiments, the retained logging residues enhanced seedling growth. In contrast, the quantity of logging residues had no discernible impact on tree growth or stand characteristics in the pine experiments. Nevertheless, the first ten-year period following the final felling may be insufficient to fully elucidate the impact of the treatments.

This study is a follow-up to Smolander et al. (2015) and extends the monitoring period to 20–21 years following the final felling. As previously stated, our hypothesis is that the impact of logging residue retention on stand productivity and soil C and N levels will become evident over time as the stands mature. Furthermore, we incorporated an older experiment that was not included in the study by Smolander et al. (2015). In that experiment, the logging residue treatments were established in conjunction with an intermediate thinning 20 years ago. In this experiment, four years after the thinning, the composition of soil organic matter and the C and N cycling were found to be affected by the quantity of residues (Smolander et al., 2013). We hypothesised that the effects of logging residue level on stand growth and soil C and N amounts would be more pronounced than after a final felling. The objective was to ascertain whether the accumulation of C and N in the humus layer is dependent on the intensity of logging residue harvesting over the long term.

2. Material and methods

2.1. Young stands after final felling

The material of the young stands comprised six experiments, two of which were Scots pine and four Norway spruce (Table 1). They were planted using containerised seedlings, following the final felling of a mature stand in 2002 or 2003. In Experiments 742 and 744, the planting density was 1.5 m × 1.5 m, i.e., 4444 seedlings ha^{-1}. In the other experiments, the planting density was 1.0 m × 1.0 m, i.e., 10,000 seedlings ha^{-1}. The pine experiments were on sub-xeric sites (i.e., on relatively infertile sites; Cajander, 1949), and the spruce experiments were on mesic heath sites (i.e., on medium fertile sites; Cajander, 1949). The soil texture was medium coarse or coarse grain, with evidence of podsolisation.

The treatments were as follows: whole-tree harvesting (R0), whereby the stems and logging residues (tree tops, branches, and needles) were removed; stem-only harvesting (R1), whereby the stems were harvested but the logging residues were left on the plots; and stem-only harvesting with a double amount of logging residues left on the plots (R2). The quantity of logging residues (estimated according to Hakkila et al. 1998) was 11–18 Mg ha^{-1} and 39–54 Mg ha^{-1} on the pine and spruce R1 plots, respectively. The double amounts of residues were obtained by relocating the residue from an adjacent R0 plot to a R2 plot. The treatments were replicated four times (in Experiment 742, three times) in a fully randomised block design in each experiment, with the size of the plots being 8 m × 8 m. Further details of the experiments can be found in Smolander et al. (2015).

In the autumn of 2022, 20–21 years after the planting, the stem diameter at breast height (1.3 m) and the height of all the trees on the plots were measured. Subsequently, the volume and biomass of the stems were estimated using the equations of Laasasenaho (1982) and Repola (2009), respectively.

2.2. Middle-aged stand after thinning

The Scots pine stand in central Finland (No. 746, Kannonkoski, N 62°.951 E 25°.204) was naturally regenerated in 1970. The soil was podzolised coarse till, and the site was designated as sub-xeric (i.e., relatively infertile; Cajander, 1949). The stand was thinned from below in 2004, in accordance with the thinning guidelines for forestry practice (Rantala, 2011), resulting in an approximate reduction of the stand basal area by 30 %.

In connection with the thinning conducted in 2004, four treatments of logging residue were established with a radius of 2.5 m around the individual sample trees. The residue levels were set at 0, 10, 20, and 30 Mg ha^{-1} by weighing the residues, with 12 replicates in a fully randomised block design. In autumn 2022, the stem diameters at breast height and the height of the sample trees were measured. In addition, increment cores were taken from the trees in every second block (i.e., six

Table 1
The average stem diameter and height of the young stands after final felling by experiment and treatment. Treatments marked with the same letter are not significantly different ($P < 0.1$).

Exp.	Tree species	D1.3, cm				H, m			
		R0	R1	R2	*p*	R0	R1	R2	*p*
740	Pine	7.5a	7.5a	8.0a	0.571	5.8a	5.7a	5.9a	0.724
742	Pine	8.5a	8.9a	9.2a	0.235	5.9a	5.7a	6.1a	0.100
741	Spruce	6.1a	6.6b	6.7b	0.002	7.4a	8.1b	8.1b	0.016
743	Spruce	6.5ab	6.8b	6.2a	0.006	7.1a	7.1a	6.8a	0.362
744	Spruce	9.4a	9.3a	9.5a	0.840	7.7a	8.5b	8.6b	0.011
745	Spruce	6.9a	7.3a	7.0a	0.179	7.8a	8.1a	7.8a	0.314
All pine exps.		8.1a	8.3a	8.8a	0.109	5.9ab	5.7b	6.1a	0.091
All spruce exps.		6.8a	7.3b	7.1b	< 0.001	7.5a	7.9b	7.8b	0.003
All experiments		7.0a	7.5b	7.4b	< 0.001	6.9a	7.2b	7.2b	0.016

Logging residue levels: R0, no logging residue; R1, normal amount of logging residue; R2, double amount of logging residue.

blocks, a total of 24 trees). The radial increments of the cores were cross-dated visually, and the ring-widths were measured with an accuracy of 0.01 mm using the WinDENDRO™ software (Regents Instruments Inc., Quebec, Canada). The impact of logging residue levels on soil properties and organic matter composition four to five years after the establishment of the experiment is reported in Dighton et al. (2012) and Smolander et al. (2013).

2.3. Soil samples and chemical analyses

Soil samples were collected during the autumn of 2022. In the young stands after final felling, ten soil cores were systematically taken from each plot using a soil auger (diameter 58 mm). Initially, spot soil preparation was carried out by manual hoeing, and the samples were taken from untreated area. The thickness of the humus layer (i.e., the organic layer including the fermented and humic layers (F+H), excluding the litter layer) was measured, and it was separated from the litter and mineral soil layers. The samples of the humus layer were combined to create a single composite sample for each plot. The composite samples were transported to the laboratory in plastic bags and stored at −18°C prior to further processing. The samples were smelt, dried at 60°C, and sieved through a 2-mm mesh size sieve. Subsequently, the pH was determined from the water-soil mixture. The total C and N contents were measured by dry combustion using a CHN analyser, as described by Soronen et al. (2024). The minimal presence of carbonates in Finnish forest soils justifies the assumption that the total C is comprised exclusively of organic carbon. The weight of the sieved dry soil was related to the area of the 10 cores, thus enabling the estimation of the C and N stocks in the humus layer per unit area.

In the middle-aged pine stand after thinning, soil samples were collected around the same trees from which the increment cores were taken, i.e., from six blocks. Four soil cores were systematically taken at a distance of 1–1.5 m from the tree stem, and subsequently combined to form a composite sample for each tree. The further processing of the samples was conducted as described above.

2.4. Statistical analyses

The statistical significance of the differences in stand and tree characteristics and soil properties among the treatments was tested using a mixed model analysis with the Mixed procedure of SAS, version 9.4 (SAS Institute Inc, 2023). In the analysis of the young stands after final felling, the models incorporated a fixed effect for the treatments and the experiments. Furthermore, the models incorporated random effects for the blocks within the experiments, but these were excluded as the majority of models with random block effects failed to converge.

In analysing the middle-aged stand after thinning, the models included a fixed effect for the treatments and a random effect for the blocks. Moreover, a continuous covariate, measured at the establishment of the experiment, was employed, namely stem diameter or tree height. In the absence of pretreatment values for soil properties in either data set, no covariate was used. As the treatments were replicated in each experiment in a fully randomised block design, it is unlikely that possible differences in initial soil properties would influence the differences between the treatments.

Pairwise comparisons were conducted by calculating the generalised least-squared means of the treatment effects. The adjusted *p*-values for the multiple comparison were calculated from the simulated distribution of the maximum or minimum value of a multivariate *t* random vector. A $p < 0.1$ was considered as a statistically significant difference.

3. Results

3.1. Young stands after final felling

The varying levels of logging residue in the young pine stands after final felling did not result in any statistically significant differences in stem diameter (Table 1). Conversely, the stem diameter of the young spruce trees was lower on the R0 plots, i.e., on the plots from which logging residues were removed. However, no statistically significant difference in stem diameter was found between the plots with the normal and double residue levels (R1 vs. R2). Similarly, in the young spruce stands after final felling, a similar kind of difference in tree height was found, as with the difference in stem diameter. The trees were shorter on the R0 plots compared with the R1 and R2 plots (Table 1). In the pine stands, the differences in tree height between the treatments did not entirely align with those observed in the spruce stands, i.e., the trees were the tallest on the R2 plots of pine, while the shortest on the R1 plots.

The results on stem volumes and biomasses were in accordance with those on stem dimensions (Table 2). In the pine stands, the stem volumes and biomasses exhibited the lowest average values on the plots from which logging residues were removed (R0), yet the differences between the treatments were not statistically significant. In the spruce stands, the volumes and biomasses were found to be significantly lower on the R0 plots. However, the stem volumes and biomasses were observed to be approximately similar on the plots with the normal and double residue levels (R1 vs. R2, Table 2).

The logging residue treatments resulted in only minor differences in the thickness of the humus layer and its C and N amounts (Fig. 1). However, the humus layer beneath the logging residues was significantly thicker than that without logging residues. The quantity of logging residues had no impact on the pH or C-to-N ratio in the humus layer. The pH was approximately 4.5, and the C-to-N ratio approximately 30 in all residue treatments. Some level differences were observed in the examined variables between the tree species, with the amount of N being lower and the C-to-N ratio being higher in the pine than in the spruce experiments. However, no such differences were found between the treatments in the pine and spruce stands (Supplementary material, Fig. S1).

Table 2
The average number of stems, as well as the volume and biomass of stems in the young stands after final felling by experiment and treatment. Treatments marked with the same letter are not significantly different (P < 0.1).

Exp.	Tree species	Number of stems, ha^{-1}				Stem volume, m^3 ha^{-1}				Biomass, Mg ha^{-1}			
		R0	R1	R2	*p*	R0	R1	R2	*p*	R0	R1	R2	*p*
740	Pine	1367a	1602a	1328a	0.428	81a	95a	80a	0.460	13.9a	17.6a	15.7a	0.778
742	Pine	3177a	3333ab	3646b	0.072	193a	204a	224a	0.057	42.9a	47.7ab	55.0b	0.065
741	Spruce	5273a	6172a	6094a	0.118	300a	354a	351a	0.105	51.9a	72.7a	73.2a	0.140
743	Spruce	4375a	4844a	5430a	0.403	250a	279a	309a	0.415	46.9a	57.5a	53.6a	0.539
744	Spruce	1680a	2969b	2891b	0.020	102a	180b	176b	0.022	39.0a	68.7b	69.7b	0.066
745	Spruce	5703a	5391a	5234a	0.815	329a	314a	303a	0.822	73.7a	78.8a	70.7a	0.913
All pine exps.		2143a	2344a	2321a	0.386	129a	142a	141a	0.332	26.3a	30.5a	32.6a	0.228
All spruce exps.		4258a	4844b	4912b	0.071	245a	282b	283b	0.054	52.9a	69.4b	66.8b	0.036
All experiments		3614a	4083b	4124b	0.039	210a	239b	241b	0.027	44.8a	57.6b	56.4b	0.016

Logging residue levels: R0, no logging residue; R1, normal amount of logging residue; R2, double amount of logging residue.

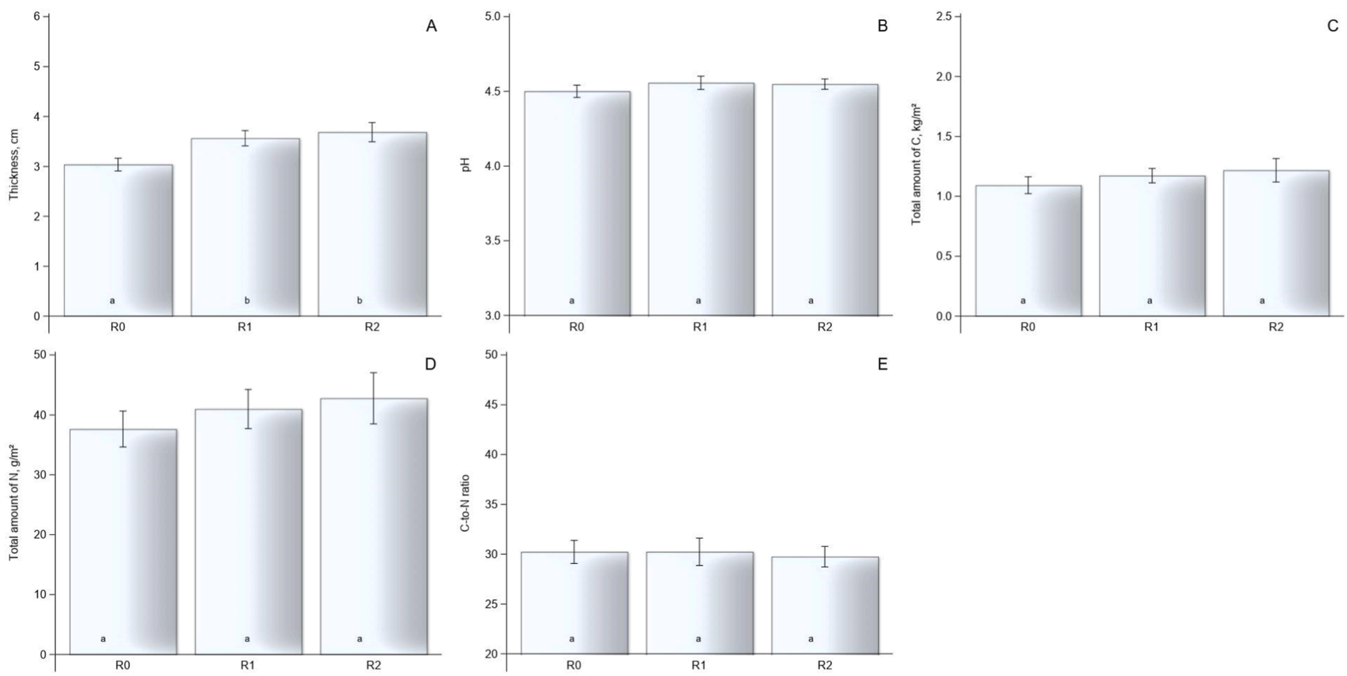

Fig. 1. The properties of the humus layer in the young stands after final felling. The logging residue levels are as follows: R0, no logging residue; R1, normal amount of logging residue; R2, double amount of logging residue. Treatments marked with the same letter are not significantly different (P < 0.1).

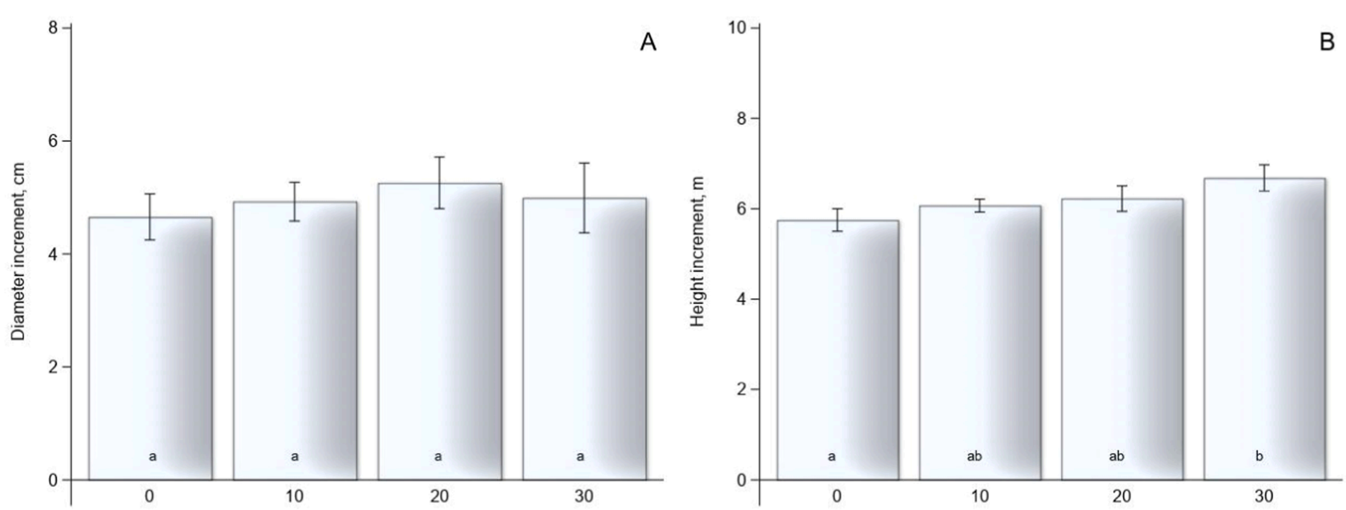

Fig. 2. The average diameter and height increment of the sample trees and their standard deviation in the middle-aged stand after thinning during the measurement period (2004–2022). The logging residue levels are 0, 10, 20, and 30 Mg ha^{-1}. Treatments marked with the same letter are not significantly different (P < 0.1).

3.2. Middle-aged stand after thinning

In the middle-aged pine stand after thinning, the varying levels of logging residue (0, 10, 20, and 30 Mg ha^{-1}) resulted in no statistically significant differences in stem diameter increment and height increment between the treatments during the measurement period (2004–2022; Fig. 2).

The annual radial increments of the sample trees decreased with increasing tree age (Fig. 3). The declining trend was interrupted by the thinning conducted in 2004. The growth-promoting impact of the thinning was sustained for approximately ten years. Following the treatment, the annual radial increments were the lowest in the trees that had been subjected to logging residue removal, although their radial increments were already the lowest prior to the thinning (Fig. 3). Furthermore, no straightforward relationship was found between the annual increment rates and the quantity of logging residues around the sample trees. In particular, the sample trees with 10 Mg ha^{-1} of residues had the highest increment rate following the treatment.

All logging residue levels increased the thickness of the humus layer and its C and N contents compared to the control. However, the differences observed between the residue levels of 10, 20 and 30 Mg ha^{-1} were small (Fig. 4). The residues resulted in a slight decline in pH, with a reduction from approximately 4.3 to 4.1. The C-to-N ratio was approximately 40 in all treatments except the 20 Mg ha^{-1} treatment, where the ratio was approximately 43.

4. Discussion

The results of this study support our first hypothesis that the extraction of logging residue from Norway spruce stands following the final felling results in a negative growth response over the longer term, despite only slight differences in growth between the logging residue levels during the first ten-year period following the planting (Smolander et al., 2015). Nevertheless, the doubling of logging residue did not result in a further growth increase in comparison with the conventional amount of logging residue. In contrast, no treatment effects were observed in the Scots pine stands, both in the young stands after final felling and in the middle-aged stand after thinning.

The results of this study are consistent with those of previous reviews in the Nordic countries, indicating a negative growth response following the removal of logging residues in Norway spruce stands. Conversely, growth in Scots pine stands has been largely unaffected (Egnell, 2017; Ranius et al., 2018). In a meta-analysis conducted on a global scale, Achat et al. (2015) concluded that the extraction of logging residues

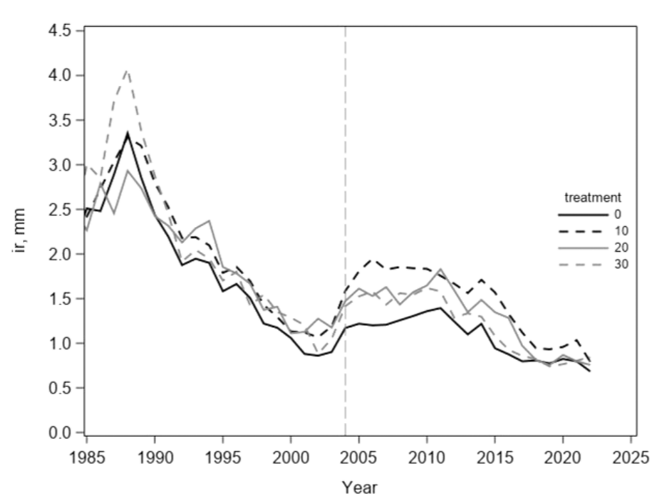

Fig. 3. The average annual radial increments of the sample trees in the middle-aged stand after thinning (the vertical dashed line). The logging residue levels are 0, 10, 20, and 30 Mg ha^{-1}.

resulted in a reduction in growth by 3 %–7 %. Furthermore, Jacobson et al. (2000) demonstrated, based on a Nordic experiment series in first-thinning stands, that whole-tree harvesting reduced volume increment in Norway spruce and Scots pine stands by 5 %–6 %. Accordingly, Helmisaari et al. (2011) observed a reduction in growth for both the 0–10 and 11–20 year periods following the whole-tree harvesting of Norway spruce thinning stands. However, a growth reduction was only observed during the second period for Scots pine. Both Jacobson et al. (2000) and Helmisaari et al. (2011) proposed that the reduction was associated with the nutrients, particularly N, that were removed in logging residues. The observed decline in the rate of net N mineralisation in middle-fertile spruce stands (Smolander et al., 2010) may also have contributed to the growth reduction. The lower quantities of logging residues harvested from Scots pine stands in comparison with Norway spruce stands may, at least in part, explain the smaller observed reactions in Scots pine (Tamminen and Saarsalmi, 2013).

In contrast with our second hypothesis, no discernible growth response was observed to the quantity of logging residues left in the thinning of the middle-aged Scots pine stand, despite the assumption that the remaining trees would respond to the nutrients released from the residue. In contrast, Egnell (2017) found in a Nordic review study that the removal of logging residue resulted in more consistent growth reductions after thinning than after final felling. In another review study, Ranius et al. (2018) reported that a growth reduction following residue extraction in thinning was observed in approximately one-third of the studies, whereas growth was not affected in the majority of studies. Accordingly, Helmisaari et al. (2011) observed considerable variation in growth reactions both between and within experiments. Similarly, Thiffault et al. (2015) concluded that there is no consistent effect of biomass harvesting on soil productivity. Furthermore, the removal or retention of logging residues gives rise to changes that extend beyond the chemical composition of soil. These encompass changes in the physical environment and competition with ground vegetation, which may prove more significant for the growth of young seedlings than the availability of nutrients in the soil.

In the young stands after final felling, the logging residues had no significant impact on the amounts of humus layer C or N. In a study conducted ten years earlier in the same experiments, the residues, particularly the normal amount (10 Mg ha^{-1}), significantly increased the C and N amounts in the humus layer of the pine experiments, but not those of the spruce or all experiments. It should be noted, however, that roots were included in the previous determination, whereas in the present study, samples were sieved through a 2 mm sieve in order to obtain the amounts of C and N in soil organic matter.

In the middle-aged pine stand after thinning, the logging residues increased both the levels of C and N in the humus layer. Recent studies have indicated that tannins play a significant role in the sequestration of C in forest soil (Adamczyk, 2021). A soil sampling conducted on the same site 16 years earlier, namely four years after the thinning, revealed an increase in the concentration of condensed tannins in the organic matter of the humus layer with increasing levels of residues. Furthermore, changes were observed in the concentration of various terpenes (Smolander et al., 2013). An increasing effect of residues on both tannin and certain terpene concentrations was also observed in the subsequent years following the final felling of spruce stands (Smolander et al., 2024). The retention of logging residues on a site results in a C input to the soil as such, but the changes in soil organic matter composition induced by logging residues may also be a significant factor influencing the long-term sequestration of C into soil. Further investigation of this subject is warranted.

It is noteworthy that the treatments were conducted in a manner that differs from the prevailing cut-to-length harvesting operations in the Nordic countries. It is common practice in experimental studies, including this one, to apply a greater degree of biomass removal than is typical in operations in practice (Thiffault et al., 2015). In Finland, the guidelines for forestry practice recommend the retention of 30 % of

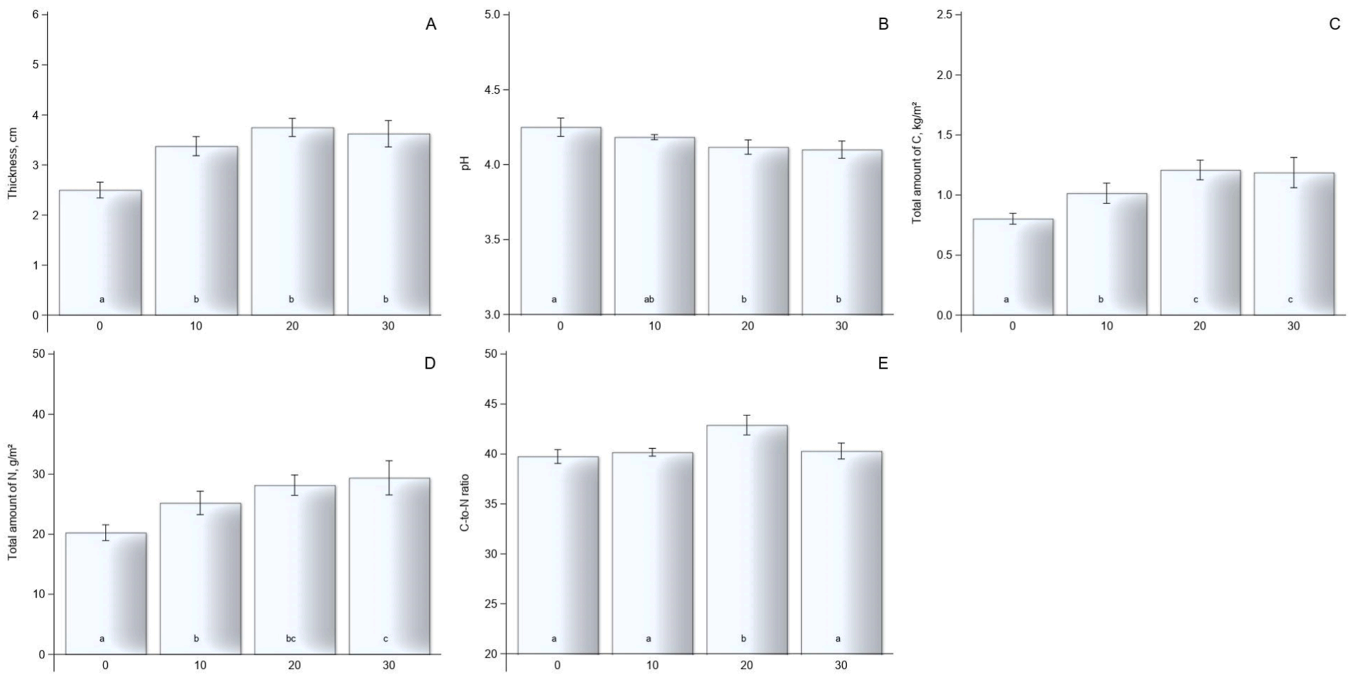

Fig. 4. The properties of the humus layer in the middle-aged stand after thinning. The logging residue levels are 0, 10, 20, and 30 Mg ha^{-1}. Treatments marked with the same letter are not significantly different ($P < 0.1$).

woody debris in the harvesting of biomass (Titus et al., 2021), in contrast to the complete removal of logging residues from the whole-tree harvesting plots. Moreover, the plot size in the experiments was relatively small, which may have reduced the differences between the treatments, i.e., probably reducing the differences of the residue levels compared to the control. Additionally, the logging residues were manually evenly distributed across the plots, rather than being left in large piles at final fellings, or along the strip roads to prevent soil compaction and to safeguard tree roots in thinnings. On the other hand, the relatively small plot size permitted the precise quantity of residues to be weighed in the middle-aged stand. Furthermore, in operational biomass harvesting, logging residues are transported with a forwarder in a subsequent operation, which results in additional soil disturbance. Moreover, in the middle-aged stand after thinning, the reactions of individual trees to different treatments were studied, rather than examining stand growth. Therefore, our experiment differs from several previous studies.

In conclusion, the removal of nutrients following the harvest of logging residue in final felling and thinning does not indicate significant issues with regard to the availability of nutrients, based on the data on tree growth. Nevertheless, a long-term decline in growth was observed in the spruce stands following the removal of logging residues in the final felling, despite the absence of major effects during the first ten-year period following planting. The smaller growth responses observed in the pine stands after final felling are likely attributable to the lower quantities of residues and, consequently, to the lower nutrient removal in residue harvesting. The impact of logging residues on the content of C and N in the humus layer was variable. In the middle-aged pine stand after thinning, a slight increase was observed, while no clear effect was evident in the young stands after final felling. Further investigation is required to determine whether this phenomenon can be attributed to a slower decomposition rate of the residues in the thinned stand or to some other factors.

CRediT authorship contribution statement

Smolander Aino: Writing – review & editing, Project administration, Investigation, Funding acquisition. **Mäkinen Harri:** Writing – original draft, Investigation, Formal analysis, Data curation, 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.

Acknowledgements

The study was conducted at the Natural Resources Institute Finland (Luke) with the support of grants from the Research Council of Finland (grant numbers 347782 and 348014). The field experiments were established by Dr. Pekka Tamminen, Dr. Anna Saarsalmi and Erkki Salo. We would like to express gratitude to Ismo Kyngäs and Veijo Salo for their invaluable contributions to the fieldwork, and to the laboratory staff at Luke for their dedication and expertise in the laboratory work.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122526.

Data availability

Data will be made available on request.

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