Scandinavian Journal of Forest Research

ISSN: 0282-7581 (Print) 1651-1891 (Online) Journal homepage: www.tandfonline.com/journals/sfor20

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To cite this article: Christian Kuehne, Aksel Granhus & Rasmus Astrup (2025) Assessing the profitability of thinning Norway's spruce and pine forests: an analysis accounting for machine trail effects, Scandinavian Journal of Forest Research, 40:1, 41-51, DOI: 10.1080/02827581.2024.2446281

To link to this article: https://doi.org/10.1080/02827581.2024.2446281

Published online: 31 Dec 2024.

SCANDINAVIAN JOURNAL OF FOREST RESEARCH
2025, VOL. 40, NO. 1, 41–51
https://doi.org/10.1080/02827581.2024.2446281

Assessing the profitability of thinning Norway's spruce and pine forests: an analysis accounting for machine trail effects

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ABSTRACT

This study examined the economic potential of thinning in pure, even-aged Norway spruce and Scots pine forests in Norway based on simulated stand dynamics using plot data from the Norwegian national forest inventory. Simulated management scenarios included fully mechanized thinning from below of varying intensity including no thinning. The economic evaluation was based on comparing the equivalent annual annuity of the unthinned scenario and the economically best-performing thinning scenario for each studied plot. The findings suggest that only late thinnings in well-stocked stands with sufficiently large trees are economically beneficial. Furthermore, to be economically superior, a thinning intervention itself had to generate enough profit, meaning that the revenue from thinning needed to sufficiently exceed the costs. Profitability of thinning scenarios varied with discount rates and timber prices and depended on whether rotation age was based on maximum net present value or maximum mean annual increment. Thinning was less often profitable in pine compared to spruce stands. This study is among the few that model stand development considering post-thinning stand structures with systematic machine trails while assessing the profitability of such thinning operations.

ARTICLE HISTORY
Received 11 October 2024
Accepted 17 December 2024

KEYWORDS
Forest management; economic feasibility; stand dynamics; growth simulation; extraction roads; sawtimber proportion

Introduction

Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.) are the most economically important tree species in Norway. While accounting for about 63% of the productive forest area (Svensson et al. 2021), approximately 98% of the annual harvest comes from forests of these two conifer species (SSB 2024a). Standard silvicultural practices for even-aged management of Norway spruce and Scots pine stands throughout Central Europe often include several commercial thinnings, mostly conducted as thinning from above prior to final felling. In Norway, thinning practices diverge from the Central European norm and conifer stands most frequently have none or only one thinning from below (Søgaard et al. 2017).

Although the interest in thinning has increased in areas with higher forest productivity and existing forest road infrastructure in recent years, the annual harvest volume coming from thinning in Norway is still fairly low. Out of the total national harvests, approximately 10% of this volume come from thinning (SSB 2008; Stokland et al. 2020) while the equivalent number in Sweden is circa 30% (Helander 2015). Hence, the question is if the Norwegian forest owners can increase the frequency of thinning operations across more stands to increase the overall economic return from their managed spruce and pine forests.

Thinning from below does not generally increase total stand volume increment over the course of an economic rotation period but can increase total merchantable volume while reducing volume lost to mortality (Mäkinen and Isomäki 2004a; 2004b; Nilsson et al. 2010; Allen et al. 2020b). This gives the potential for increasing the stand value at the rotation age as thinning can produce a larger amount of products with greater market value. Therefore, while thinning may in some cases not initially result in profit, the stand value at the end of the rotation may be increased by thinning due to having a larger amount of higher valued products.

The vast majority of thinning operations in Norway today is conducted using the cut-to-length (CTL) method, employing single-grip harvesters and forwarders. An inherent feature of these highly mechanized thinning operations is the need to establish machine trails about 4 m wide and with a spacing that allows for trees between adjacent machine trails to be reached by the harvester crane. Inevitably, the complete tree removal along machine trails lowers the effective production area to some extent at least temporarily, although the associated growth loss may be compensated for by accelerated growth of residual trees growing adjacent to the machine trails. To our knowledge, the spatially heterogenous growth dynamics resulting from the creation of machine trails have rarely been considered when applying growth models to assess the stand-level effects of fully mechanized thinning (but see e.g. Niemistö 1989).

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Given an anticipated increased demand for small diameter products and increased pulpwood prices, thinning levels can be expected to increase in Norwegian conifer forests. An understanding of the potential for thinning in Norway and its impact on forest value is necessary for providing management recommendations. Therefore, the purpose of this work was to examine the potential for increased forest revenues in even-aged Norway spruce and Scots pine forests in Norway. The main objective was to examine the economic performance of varying levels of thinning at various stand development stages while accounting for the effect of machine trails on overall stand growth. The economic performance of the different thinning scenarios was assessed applying rotation ages corresponding to either (1) age of maximum net present value or (2) age of maximum mean annual increment.

Material and methods

This study used a multi-step modeling approach performing various prediction and simulation procedures to evaluate the economic feasibility of thinning in Norwegian conifer forests. To monetarize revenue streams from thinning interventions and final harvest operations, functions to predict stand-level proportion of merchantable volume as well as proportion of sawtimber volume thereof were derived from experimental long-term trial plot data. To realistically evaluate stand dynamics in thinned and unthinned stands, permanent plot data from the Norwegian national forest inventory were utilized as simulation starting points. Stand characteristics such as dominant height, stem density and basal area forecasted in the growth and yield simulations were then employed as inputs for the derived prediction functions to calculate merchantable and sawtimber volume proportions.

Long-term trial data for modeling merchantable and sawtimber volume proportions

The data for developing models for merchantable timber volume proportions came from a series of silvicultural trials consisting of unthinned and thinned permanent sample plots established in even-aged Norway spruce and Scots pine forests. Establishment of the trials occurred mostly in the late 1960s and 1970s in stands aged approximately 20–40 years. Within these data were 303 and 821 observations from unthinned and thinned spruce stands, respectively, and 279 and 946 observations from unthinned and thinned pine stands, respectively (Table 1). The trials are distributed across the natural ranges of Norway spruce and Scots pine within Norway, except for the western part of the country with its maritime climate. Thinning from below was the primary thinning method in these trials, i.e. removal of trees starting from the lower end of the diameter distribution. The thinning interventions were conducted manually without logging machines and resulted in a mostly uniform spacing of the residual trees. A full description of these trials is provided by Allen et al. (2020a) and Kuehne et al. (2022).

Within these long-term trial data, merchantable stem volumes of individual trees were calculated using the taper equations of Hansen et al. (2023) according to two different assortments, namely sawtimber and pulpwood. Sawtimber was specified to have a minimum log length of 3.4 m and a minimum top diameter over bark of 13.5 cm. Pulpwood was specified to have a minimum log length of 3 m and a minimum top diameter over bark of 5 cm. Stump height was set to 0.3 m. Individual tree volumes were finally summarized at the stand level.

National forest inventory data for simulating stand dynamics

The Norwegian national forest inventory (NFI) consists of a series of about 11,700 forested permanent plots, established during the period from 1986–1993 on a 3×3 km grid across most of Norway (Breidenbach et al. 2020). The permanent plots are measured every 5 years and include detailed individual tree measurements as well as information concerning silvicultural interventions. For the objectives of this study, the NFI data from the period 2016–2020 were subset to select plots in even-aged (i.e. with a single canopy layer) Norway spruce and Scots pine forest stands with no record of prior thinning, a stand density > 750 trees ha^{-1} and a stand age between 20 and 100 years. The proportion of basal area in spruce or pine, respectively, had to constitute at least two thirds for a plot to be considered here. Plots with a dominant height exceeding 20 and 22 m for spruce and pine, respectively, were excluded as initiating thinning in such stands is not recommended in Norway (Kühne et al. 2023). The subset also did not include plots from western Norway because growth and yield models used for simulating stand development in this study were derived without data from that region. In total, 146 spruce plots and 79 pine plots were used covering a wide range in stand age, stand density and tree size (Table 2).

Modeling approach for predicting volume proportions

Modelling of stand-level sawtimber volume proportions for both examined tree species was carried out in two stages. In the first stage the proportion of nonmerchantable stand volume (PNM) as a percentage of total stand-level stem volume was modeled as a function of dominant height (average height of the 100 thickest trees ha^{-1} in m, HD) and quadratic mean diameter (QMD, cm) using a logistic function:

$$PNM = \left(\frac{1}{1 + \exp(-(X\beta))} \right) \quad (1)$$

where $X\beta$ is the model-specific explanatory variable design matrix with the associated estimated fixed parameters.

Based on the modeling of PNM, the proportion of merchantable volume (PM) in a stand can be calculated as PM = 1 − PNM.

Table 1. Long-term trial stand-level metric statistics (SD = standard deviation) for observations from unthinned and thinned stands used to model merchantable volumes including dominant height (average height of the 100 thickest trees ha^{-1} in m, HD), quadratic mean diameter (QMD, cm) and total stem volume (VOL, m^3 ha^{-1}).

	Spruce								Pine							
	Unthinned				Thinned				Unthinned				Thinned			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
HD	18.2	6.2	4.7	33.1	17.9	5.5	7.5	33.9	14.5	4.0	6.8	30.5	16.0	4.5	6.1	30.8
QMD	15.3	5.0	3.6	29.6	18.0	5.5	6.8	34.1	13.1	2.9	7.0	26.3	16.3	5.1	7.2	40.2
VOL	352.8	214.4	3.7	1044.8	264.9	169.6	17.6	939.9	192.3	123.1	34.9	651.8	192.0	105.2	16.8	727.1

Table 2. Stand-level metric statistics (SD: standard deviation) for plots from the Norwegian national forest inventory used to simulate stand dynamics with and without a thinning intervention including stand age (AGE, years), dominant height (average height of the 100 thickest trees ha^{-1} in m, HD), stem density (TPH, trees ha^{-1}), quadratic mean diameter (QMD, cm) and total stem volume (VOL, m^3 ha^{-1}).

	Spruce ($n = 146$)				Pine ($n = 79$)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
AGE	48.0	15.0	23	95	56.8	17.0	25	96
HD	16.4	2.3	10.1	19.9	15.9	3.1	8.3	21.9
TPH	1673.4	542.7	760	3600	1419.2	506.9	760	3000
QMD	14.5	2.6	8.1	21.6	15.5	3.0	8.9	23.4
VOL	184.1	70.4	72.6	369.3	185.7	78.3	83.4	448.2

In the second stage and in similar fashion to PNM, the proportion of sawtimber (PST), calculated as a percentage of total merchantable volume, was also modeled as a function of HD and QMD. Consequently, the proportion of pulpwood (PPW) in merchantable volume can be calculated as PPW = 1-PST.

Simulation of stand development

Stand development of each selected NFI plot was simulated using the stand-level growth and yield models of Allen et al. (2020a) and Kuehne et al. (2022) developed for forecasting stand dynamics of thinned and unthinned Norway spruce and Scots pine forests in Norway, respectively. These growth and yield models consist of individual equations for stand-level volume, dominant height growth, basal area growth, and survival and were developed from the same long-term thinning trial data as presented in Table 2.

For each NFI plot, eight thinning scenarios were simulated including no thinning and single, fully mechanized thinnings from below removing 20, 25, 30, 35, 40, 45, or 50% of the basal area at the very beginning of a simulation run. Consequently, the simulations of thinned stands incorporated only a single thinning intervention, which was conducted at the stand age as recorded for each respective NFI plot. Fully mechanized cut-to-length (CTL) forest operations are the norm in managed Norwegian conifer forests and this study thus aimed to model the comprehensive employment of forest machinery. To properly simulate fully mechanized thinning operations, simulated tree removal began with the complete creation of the machine trail network, i.e. the removal of trees along trails. Individual trails were assumed to be 4 m wide and with a spacing of 20 m from centerline to centerline accounting for 20% of the total stand area. Assuming a uniform distribution of trees across stands, the creation of the machine trail network thus removed 20% of stand-level basal area and stem volume, without affecting the quadratic mean diameter. Consequently, thinning intensities below 20% basal area removal were not evaluated and only thinning intensities > 20% basal area removal resulted in tree felling between the machine trails. Tree removal between trails was assumed to be conducted as thinning from below and to result in uniform post-thinning tree spacing. To account for the distinct stand structure resulting from fully mechanized thinning, simulations using the aforementioned stand-level growth and yield models for thinned stands had to be adjusted accordingly. Stand dynamics in thinned stands were thus forecasted by running two simulations simultaneously. Simulations were run for (i) stand areas affected by machine trails, i.e. where residual trees would gain access to additional resources as a result of creating the trails and (ii) stand areas not effected by trails. It has been shown that depending on stand conditions, linear clearings such as trails can increase the diameter growth of residual forest trees up to 3–5 m away from the outer edge of a trail (see overview in Bowering 2004; Mäkinen et al. 2006). To account for this growth effect, this study defined areas affected by trails as the combined areas covered by the cleared trails as well as 4 m forest edge strips running immediately adjacent on each side of a trail. Areas affected by trails thus accounted for 60% of a stand in the simulations of this study. Stand development in the different areas were simulated separately as the basal area removal varied between the stand areas affected and not affected by trails. Basal area removal of areas influenced by trials were thereby quantified as area weighted mean of the cleared trails (100% basal area removal) and the adjacent forest edge strips (varying basal area removal depending on thinning intensity of simulated thinning scenario). For example, the mere creation of the machine trail network with a total basal area removal of 20% at the stand level would result in a removal of 33.33% and 0% for the trail-affected and trail-unaffected stand areas, respectively. Note that applying the aforementioned growth and yield models by Allen et al. (2020a) and Kuehne et al. (2022) assumes uniform spacing between residual trees after the thinning intervention in trail-unaffected as well as trail-affected areas. There is, however, no uniform spacing in the areas affected by machine trails given the complete clearing along trails. Despite this deviation from the ideal application of the implemented growth and yield models, we believe that our approach is more realistic than assuming uniform spacing across the entire stand (i.e. similar spacing in trail-affected as well as trail-unaffected areas) or assuming no timber production on the cleared trails (cf. Kuliešis et al. 2018). The increase in growth rates of trees in proximity of clearings including machine trails varies with distance to the clearing (Mäkinen et al. 2006; Kuehne et al. 2018). Therefore, predicting stand-level growth as proposed and performed here is likely quite accurate, as substantially higher growth rates in trees close to the machine trail offset the more moderately increased growth of trees farther away from the trail. Since the underlying stand-level growth and yield models applied in the simulations run on hectare-based input variables, the simulations also produced hectare-based outputs. Results of the two separate simulation runs were thus merged and jointly appraised after each simulation step by calculating area weighted stand-level metrics. To simulate realistic thinning scenarios, the residual basal area following thinning was restricted to be no less than 12 m^2 ha^{-1}. The simulations were carried out in 1-year time steps for 100 years.

Economic evaluation

Following simulation, the net present value (NPV, NOK ha^{-1}) for each plot at each time step in each thinning scenario was calculated to monetarize total timber volume production over an entire rotation including timber removed during a thinning as follows.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+r)^t} \tag{2}$$

where Rt is the net cashflow at stand age t, n is the total number of years (rotation length) and r is the discount rate. R_t at each time period was calculated based on the standing volume and any volume removed in the simulated single thinning intervention including no thinning. Additional costs associated with stand establishment (site preparation, planting) and pre-commercial thinning were not considered in this analysis because these costs would be shared and thus the same in different thinning scenarios for the same plot. To determine optimal rotation age for each stand and management scenario, two different approaches were applied. First, optimal economic rotation length was defined as the harvest age of an individual thinning scenario and a certain plot where NPV is maximized (i.e. maximum sustainable revenue). Second, optimal biological rotation age was defined based on maximum mean annual stand-level volume increment (MAI, i.e. maximum sustainable yield). Economic performance of thinning scenarios selected with the latter approach was also quantified and evaluated using NPV. Irrespective of the optimal rotation approach applied, different thinning scenarios (i.e. thinned vs. unthinned) for the same stand often resulted in varying rotation lengths. To compare the NPV of the different management scenarios over the resulting different rotation lengths, the equivalent annual annuity (EAA, NOK ha^{-1} yr^{-1}) approach was used (Ahtikoski et al. 2004; Bullard and Straka 2011). EAA is derived from and expresses a specific NPV as annual cashflows so that the present value of all annual cashflows over a rotation equals the overall NPV (of a certain management scenario). EAA was calculated as follows:

$$EAA = \frac{NPV*r}{1-(1+r)^{-T}} \tag{3}$$

where T is stand age at the time of final felling (rotation length) and all other variables have been defined above. Once the optimal rotation age was defined based on maximum NPV or maximum MAI, respectively, the corresponding NPV was transformed to EAA. The thinning scenario with the highest EAA for a certain plot was then selected to be compared with the EAA of the corresponding scenario without thinning. We finally calculated the relative difference between the EAAs of the best-performing thinning scenario and the scenario without thinning as follows:

$$relEAA = 100*(EAA_{THIN} - EAA_{UNTHIN})/EAA_{UNTHIN} \tag{4}$$

where relEAA is the relative EAA difference in %, EAA_{THIN} is the EAA of the best-performing thinning scenario for a certain studied plot and EAA_{UNTHIN} the EAA of the corresponding scenario without thinning for the same plot. A positive relEAA implies that the selected thinning scenario is economically more favorable than the scenario without thinning.

NPV and EAA were quantified using average pulpwood and sawtimber prices of 255 and 467 (spruce) as well as 236 and 460 NOK per m^3 (pine), respectively (2006–2022; SSB 2024b). In a high price simulation run, pulpwood and sawtimber prices were set to 344 and 654 (spruce) as well as 328 and 624 NOK per m^3 (pine), respectively (SSB 2024b). Thinning and final harvesting costs including equipment mobilization, cutting and forwarding to the landing were set to 250 and 200 NOK per m^3, respectively. The discount rate was set to 1, 2.5 or 4%.

Results

Prediction of timber volume proportions

PNM for unthinned and thinned spruce stands ranged from 0.002 to 0.965 and 0.002 to 0.536, with means of 0.056 and 0.029, respectively. PST for these spruce stands varied between 0 and 0.949 for unthinned stands, and between 0 and 0.965 for thinned stands, with means of 0.482 and 0.575, respectively. Similarly, PNM for unthinned and thinned pine stands ranged from 0.003 to 0.349 and 0.001 to 0.280, with means of 0.033 and 0.013, respectively. PST for these pine stands varied between 0 and 0.912 for unthinned stands, and between 0 and 0.981 for thinned stands, with means of 0.313 and 0.466, respectively.

HD and QMD exhibited strong relationships with PNM and PST (data not shown). Irrespective of species, the best-performing logistic models to predict PNM and PST therefore included the reciprocal of HD and the reciprocal of QMD (Table 3). Thinning appeared to slightly increase PST, at later stand development stages in particular, i.e. with increasing HD and QMD, respectively. Consequently, an indicator

Table 3. Parameter estimates (standard errors) for tree species-specific logistic regression models predicting nonmerchantable volume (PNM) as a proportion of total stand-level stem volume and sawtimber volume (PST) as a proportion of stand-level merchantable volume. Predictors include dominant height (HD, m), quadratic mean diameter (QMD, cm) and a binary indicator variable indicating whether a stand was thinned (THIN).

	Spruce PNM	PST	Pine PNM	PST
Intercept	−7.451 (0.024)	5.061 (0.053)	−7.277 (0.032)	4.971 (0.101)
1/HD	4.667 (0.541)	−24.654 (1.146)	10.759 (0.457)	−16.829 (1.275)
1/QMD	46.612 (0.489)	−52.260 (1.162)	36.067 (0.497)	−58.442 (1.646)
THIN		−0.811 (0.064)		−0.853 (0.093)
THIN:HD		−0.038 (0.005)		−0.032 (0.006)
THIN:QMD		0.085 (0.005)		0.073 (0.006)
MB	0.00067	−0.00760	0.00164	−0.00917
MAB	0.00488	0.02662	0.00534	0.03912

variable for thinning in conjunction with interactions with HD and QMD improved prediction accuracy of the PST models for both species (Table 3). The models performed better for thinned stands but did not result in any obvious major bias (Figure 1).

Simulation of stand dynamics and economic evaluation

Simulating stand development of even-aged single-species spruce and pine stands assuming fully mechanized felling operations revealed differences between the scenarios with thinning based on maximum NPV and the scenarios based on maximum MAI. Basal area removals for the best-performing thinning scenarios based on maximum NPV averaged close to 20% with very low variation irrespective of discount rate, timber prices and studied species. In contrast, average basal area removal levels for the best-performing thinning scenarios based on maximum MAI increased from 20% to 30% and from 26% to 35% for spruce and pine, respectively, with increasing discount rate and timber prices. Thinning increased rotation length by an average of 3 and 6 years for spruce and pine, respectively, regardless of whether comparisons were based on maximum NPV or maximum MAI. The average difference increased to about 20 years when comparing rotation lengths for the scenarios selected based on maximum NPV vs. maximum MAI – irrespective of species, management scenario (thinning vs. no thinning), and discount rate.

Ignoring the outlined difference in rotation length between management scenarios, average MAI at the end of simulated rotations was in general lower for thinned stands compared to unthinned stands in spruce. In contrast, an opposite pattern was found for pine. Differences in MAI were smaller for simulations based on maximum NPV compared to scenarios derived from maximum MAI. However, MAI differences were generally small with little variation in pine (on average 0.02 $m^3\ ha^{-1}\ yr^{-1}$) while an increasing discount rate resulted in increasing mean MAI differences (from −0.07 to −0.18 $m^3\ ha^{-1}\ yr^{-1}$), i.e. higher production losses for spruce. QMD at the end of simulated rotations was on average about 2 cm higher for thinned stands compared to unthinned stands, irrespective of species. Differences in QMD were slightly more pronounced for scenarios selected based on maximum MAI. Here, QMD increased with increasing discount rate from 0.6 to 3.6 cm (spruce) and 1.9 to 2.4 cm (pine) for medium timber prices.

Simulation outcomes further showed that, in general, thinning was less often profitable in pine stands compared to spruce stands (Table 4). A higher discount rate resulted in greater profitability of thinning scenarios for simulations based on maximum MAI for both studied species. An opposite trend was observed for simulations based on maximum NPV, with a discount rate of 4% sometimes resulting in immediate final harvest and thus no comparison of scenarios with/without thinning. Irrespective of species, an increasing discount rate also resulted in greater variation in relEAA, i.e. often amplifying relative differences found between management scenarios with and without thinning. Further, a higher discount rate also increased basal area removal levels in the best-performing thinning scenarios for simulations based on both maximum NPV and maximum MAI. Higher timber prices increased profitability of thinning regardless of species and how rotation length was defined (Table 4).

The relative economic performance of thinning scenarios was positively related to quadratic mean diameter at the time of thinning and to a somewhat lower extent to dominant height as well as basal area at the time of thinning (Figures 2 and 3). Negative relationships were found for number of stems per hectare while site quality only occasionally demonstrated a weak positive correlation with relEAA (data not shown). Further, thinnings that were sufficiently profitable, i.e. higher revenue than costs, appeared to boost the economic performance (Figures 2 and 3). The observed relationships appeared to be slightly more pronounced in pine than in spruce as well as for simulations based on maximum MAI compared to the ones based on maximum NPV. In addition, the relationships also tended to become stronger with increasing discount rate (cf. Table 4).

Discussion

In contrast to most earlier Nordic studies on the economic feasibility of thinning in Norway spruce and Scots pine, the analysis presented here accounts for the stand structure created in fully mechanized thinning operations (half-systematic thinning according to Mäkinen et al. 2006). Accounting for the concentrated removal of trees along machine trails (Hosseini et al. 2019) as compared to a more uniform removal of trees (selective thinning according to Mäkinen et al. 2006), has often not been considered in similar previous works. Because machine trails are first and foremost created when removing trees in a fully mechanized thinning intervention, the newly available growing space is not distributed to all residual trees evenly. Depending on the thinning intensity, i.e. basal area reduction level, such a thinning operation mostly promotes the growth of only those trees close to the machine trail (Mäkinen et al. 2006; Kuliešis et al. 2018). The average post-thinning tree growth is thus not as much enhanced as in a fully selective thinning with similar removal levels, resulting in an overall limited stand-level growth response (Segtowich et al. 2023). Differences in average tree size at the end of a rotation between management scenarios with and without thinning were thus not very pronounced in this study (cf. e.g. Mäkinen et al. 2006; Nilsson et al. 2010). As a result, thinned stands do not produce as much highly priced sawtimber as could be expected, which impaired their economic performance. This effect was more pronounced for management scenarios based on maximum NPV because average rotation length was much lower compared to scenarios selected based on maximum MAI. A shorter rotation period reduces the time during which trees can take advantage of the resulting enhanced growing conditions following thinning. It should be noted that the potentially enhanced growth of trees close to created machine trails is dependent on the absence of stem and root damages incurred during the thinning operation (Tavankar et al. 2022). Such injuries are often

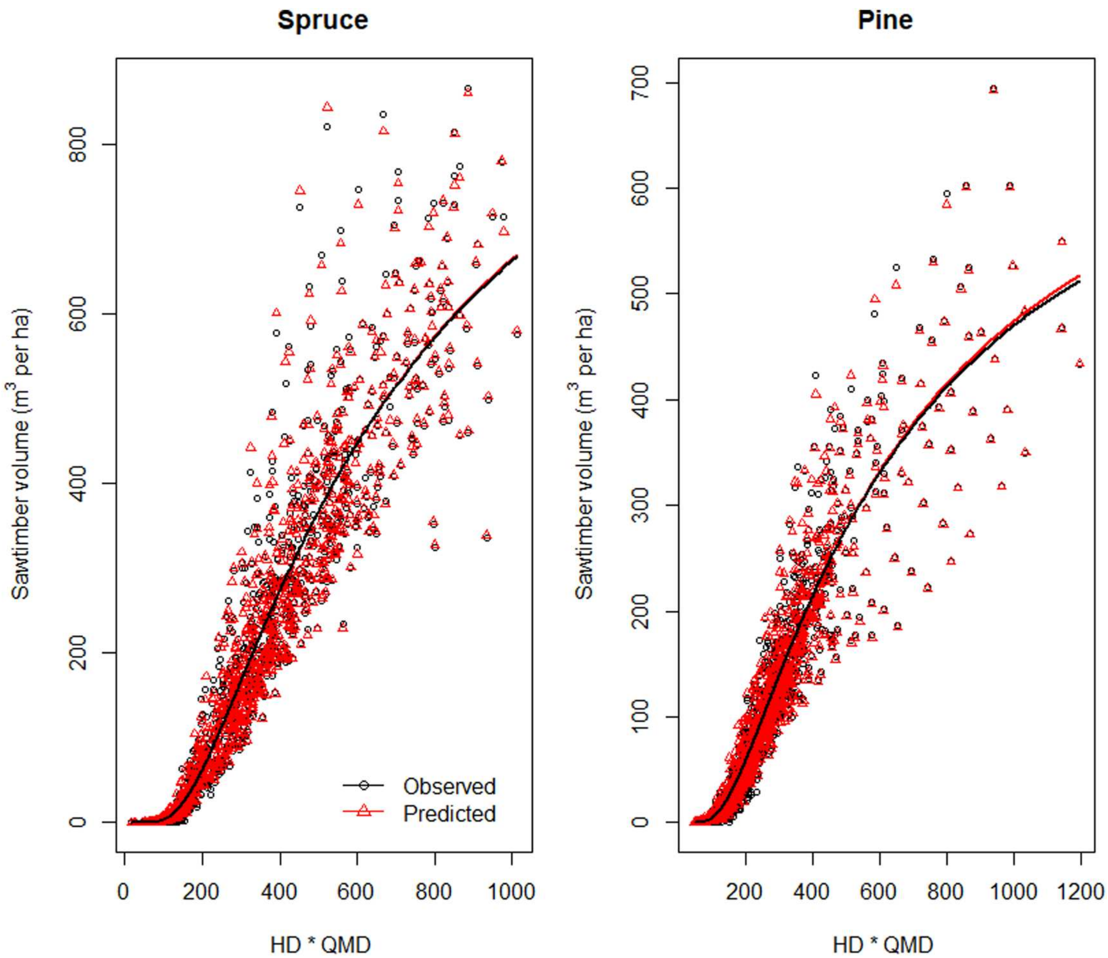

Figure 1. Comparison of observed and predicted sawtimber volumes for unthinned and thinned stands of spruce and pine, respectively, over the product of observed dominant height (HD) and observed quadratic mean diameter (QMD). Fitted lines were derived from exponential functions. Predicted sawtimber volumes were derived from species-specific logistic regression models. Stand-level merchantable volume was first quantified by predicting nonmerchantable volume quantified as proportion of total stand-level stem volume with the subsequent prediction of sawtimber volume quantified as a proportion of stand-level merchantable volume.

inevitable (Picchio et al. 2020) but were not accounted for in this study which represents a simplification. However, these damages are not restricted to trees along trails and thus, albeit to a lower extent, can also be expected in stand areas located farther away from trails (Fjeld and Granhus 1998). In addition, it has been shown that motor-manual felling in combination with skidding likely necessary in fully selective thinning interventions can cause greater damages when compared with fully mechanized CTL operations as simulated in this study (Picchio et al. 2020). Stem damages will inevitably affect future log quality and as a result sawtimber proportions. However, such data were not available for this study and, therefore, could not be factored in.

As shown at least in part here, overall net timber volume production of thinned conifer stands is often reduced over entire rotations compared to unthinned stands growing under similar conditions in Fennoscandia (Wallentin 2007). In this study, the effect was less pronounced, and occasionally inverted, in simulations involving stands of the shade-intolerant pine. This is likely attributable to the diminished production losses as a result of reduced natural mortality within thinned pine stands. Still, slightly lower overall timber production in addition to the muted stand-level growth response as described above, is likely the reason, why the profitability of a thinning intervention itself (i.e. higher thinning revenue than thinning costs) was crucial for whether a thinning scenario was economically superior (cf. Tahvonen et al. 2013). This held especially true for simulations with discount rates of 2.5% or 4% as an increasing discount rate diminishes the significance of the later final harvest revenue stream (Hyytiäinen et al. 2004; Cao et al. 2006; Fransson et al. 2020). This study thus suggests that (only) comparatively late thinnings in stands with a sufficient stocking and a minimum average tree size can have a positive economic impact. The findings indicate that this refers to a QMD of at least 15 cm and a basal area of circa 30 m^2 for both studied species. However, this general conclusion aligns more closely with the findings for scenarios based on maximum MAI compared to the scenarios based on maximum NPV. Previous similar studies also reported that late thinning interventions in well-stocked stands lead to the most favorable economic outcomes (Pukkala et al. 1998; Hyytiäinen and Tahvonen 2002). Similarly, other works stated that large trees should be removed in thinning interventions to maximize

Table 4. relEAA (relative difference in equivalent annual annuity between the best-performing thinning scenario and the corresponding scenario without thinning) statistics (Perc: percentage of plots with positive relEAA, SD: standard deviation) for stand development simulations run for spruce- and pine-dominated plots from the Norwegian national forest inventory and with varying discount rates and timber prices. Rotation lengths in the different simulations were defined according to maximum net present value (NPV) or maximum mean annual increment (MAI). A positive relEAA implies that thinning is profitable, i.e. the thinning scenario performs better than the scenario without thinning from an economic perspective.

Species	Scenario		NPV					MAI				
	Discount rate	Timber price	Perc	Mean	SD	Min	Max	Perc	Mean	SD	Min	Max
Spruce	1.0	Average	28	−1.0	1.6	−5.6	2.2	26	−0.9	1.3	−5.4	1.5
	2.5	Average	22	−1.9	2.4	−8.6	2.5	68	1.9	4.1	−6.0	18.2
	2.5	High	45	−0.4	2.0	−5.5	3.6	86	5.6	6.0	−2.2	26.5
	4.0	Average	24	−2.8	3.3	−11.5	2.4	82	14.9	16.3	−11.5	74.9
Pine	1.0	Average	33	−0.8	1.8	−7.0	3.2	27	−1.2	2.0	−7.0	2.6
	2.5	Average	19	−2.7	3.5	−15.1	4.7	20	−3.3	5.1	−16.8	14.0
	2.5	High	41	−0.7	2.4	−8.0	4.6	42	0	5.9	−10.8	24.8
	4.0	Average	19	−4.3	4.9	−22.0	3.7	38	0.3	16.7	−28.9	68.1

revenue (Hyytiäinen et al. 2004; Pukkala et al. 2015). The results were often interpreted as diverging from official thinning guidelines which schedule thinnings earlier during stand development. Considering this study's findings, this appears to hold true for Norway as well (cf. Kühne et al. 2023). Because an early successional tree species and thus less responsive to late interventions, thinning appeared to be less often profitable for pine when compared to spruce in this study (cf. Mäkinen and Isomäki 2004a, 2004b).

The findings of this study contrast the ones from Fransson et al. (2020), who reported a better economic performance of thinning from below in spruce stands when compared to management without thinning. However, Fransson et al. (2020) assumed a uniform removal of trees creating a homogenous stand structure without cleared machine trails, i.e. similar post-thinning spacing of residual trees. Fransson et al. (2020) also showed that an optimal selection of trees removed in a thinning from above can further significantly improve the economic performance – an extremely contrasting thinning scenario compared to the ones evaluated in this study which are more common in Fennoscandia (Mäkinen et al. 2006). However, it should be noted that many previous similar studies found that depending on site productivity and discount rate, thinning regimes with multiple interventions throughout a rotation were often most profitable (Hyytiäinen and Tahvonen 2002; Cao et al. 2006). Simulated management scenarios considered in this study comprised only one single thinning to better reflect the conditions under which the Norwegian forestry sector operates. Therefore, the findings presented here do not represent or suggest optimal management approaches.

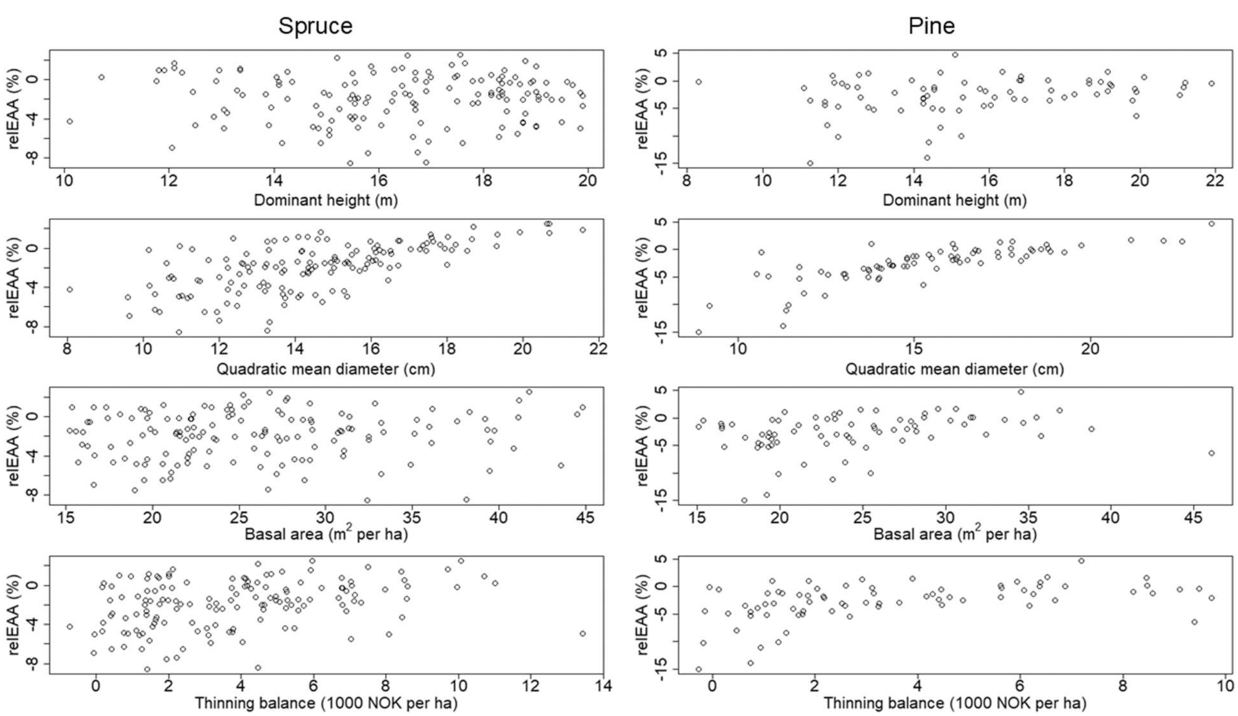

Figure 2. Relation between relEAA (relative difference in EAA of the best thinning scenario and the corresponding scenario without thinning) and dominant height, quadratic mean diameter and basal area (all referring to the time of thinning) as well as thinning balance (net profit from thinning operations at the forest landing taking into account revenues from timber sales and expenses associated with equipment mobilization, timber cutting and forwarding) for even-aged spruce and pine stands. Simulations were run with average timber prices and a discount rate of 2.5% and rotation length defined based on maximum net present value. A positive relEAA implies that the thinning scenario performs better than the scenario without thinning from an economic perspective.

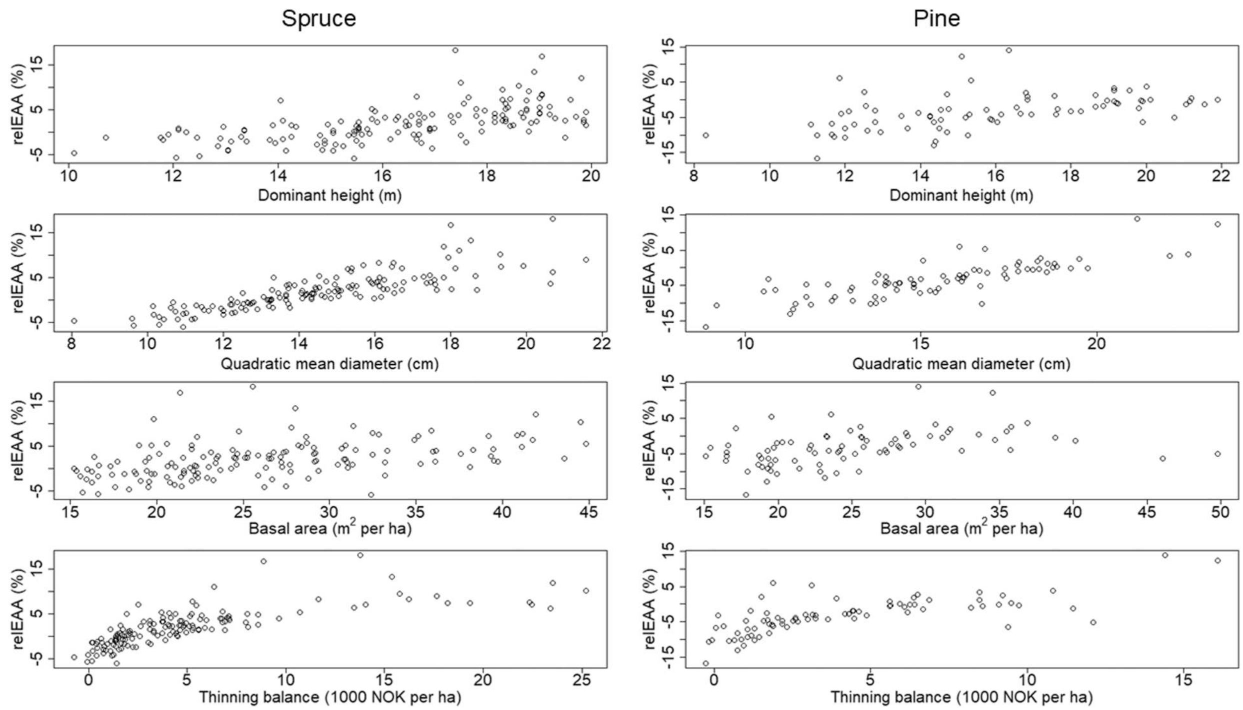

Figure 3. Relation between relEAA (relative difference in EAA of the best thinning scenario and the corresponding scenario without thinning) and dominant height, quadratic mean diameter and basal area (all referring to the time of thinning) as well as thinning balance (net profit from thinning operations at the forest landing taking into account revenues from timber sales and expenses associated with equipment mobilization, timber cutting and forwarding) for even-aged spruce and pine stands. Simulations were run with average timber prices and a discount rate of 2.5% and rotation length defined based on maximum mean annual increment. A positive relEAA implies that the thinning scenario performs better than the scenario without thinning from an economic perspective.

Timber prices and harvest costs employed to monetize forest management activities simulated in this study were rather simplistic. Although many Norwegian sawmills do no longer pay a prize premium on large-diameter logs, the price for sawtimber can for example still vary with log size (Fransson et al. 2020), but also timber quality (Tahvonen et al. 2013) and wood properties (Cao et al. 2008). Further, models have been used in the past to more accurately estimate harvest costs by considering a variety of harvest related variables (e.g. Cao et al. 2006; Ahtikoski et al. 2021). Such models often consider factors including the type of harvesting system used and associated mobilization costs, location of the harvest site including distance to forest roads, the terrain of the harvest site, and the species and size of the trees being harvested. Notably, average diameter of harvested trees and machine travel distance are factors affecting thinning costs, regardless of the harvesting system (Chang et al. 2023). By incorporating these factors, forest harvest cost models can provide a more accurate estimation of the true costs associated with forest management activities. Given its often difficult and rough terrain with steep slopes and boulders, forest operations in Norway are often comparatively cost intensive. The harvest costs utilized in this study thus predominantly pertain to sites where machinery can operate without major restrictions. Consequently, in very challenging terrain, thinning will be even less profitable than indicated here. The results of this study thus appear to indirectly corroborate that optimal management regimes are highly sensitive to the costs of harvest (Hyytiäinen and Tahvonen 2002). An additional factor to bear in mind when economically evaluating harvest operations, and thinning interventions in particular, is trucking expenses. Costs associated with transporting logs from the forest landing to the mill were outside the scope of this work but also hold significant importance in determining the economic viability of harvest operations (Kärhä et al. 2024).

Although this study found that thinning is often not economically beneficial, thinning timely scheduled and properly done can have positive effects in the mid- and long-term on stand development (Moreau et al. 2022). Enhanced resistance to for example storm (Pukkala et al. 2016), snow (Valinger et al. 1994) and drought (Navarro-Cerrillo et al. 2023) could not be incorporated in this analysis but should be taken into account in areas where such abiotic disturbance agents are a potential risk to forest management (Halbritter et al. 2020). This holds also true for some biotic threats (Roberts et al. 2020). A potential alternative to boost individual tree vigor and anchorage and thus overall stand stability would be to reforest with lower initial planting densities as suggested by Pettersson et al. (2017). Positive effects on average tree quality as a result of thinning interventions can also be expected but could also not be considered here (Pfister et al. 2007; Liziniewicz et al. 2016). Finally, stands that have been thinned in a timely and appropriate manner are also better prepared to initiate natural regeneration toward the end of the rotation. Such strategic thinning interventions enhance the windfirmness of trees and increase their potential as seed sources due to larger crowns (Slodicak et al. 2005). Catastrophic disturbance events in unthinned stands can result in total economic losses (Cameron 2002). The potential additional benefits of thinning, as listed above, thus provide a different perspective on the often small economic losses identified for the thinning scenarios of this study. However, the fully mechanized low thinning regimes evaluated here might not be the most effective approach to enhance resistance of conifer trees and stands (Pukkala et al. 2016).

Conclusions

This study is among the few that model stand development considering post-thinning stand structures with machine trails while assessing the profitability of such thinning operations. Taking into account the systematic creation of these trails as part of thinning interventions appears to be crucial as post-thinning growth patterns seem to differ compared with the ones following selective thinning with a more spatially uniform post-thinning distribution of trees. However, the stand-level approach used in simulations of this study might not be accurate enough to fully capture the varying growth response of trees in proximity of machine trails. The overall stand-level yield of thinning scenarios in this study thus may be slightly overestimated. This is a result of the employed stand-level models' inherent characteristic of assuming uniform spacing of residual trees in the machine trail-affected stand areas. Consequently, this could lead to an overestimation of actual profitability. An individual tree simulation approach based on distance dependent growth equations will likely produce more precise growth and yield predictions.

Acknowledgements

This work was supported by Utviklingsfondet for Skogbruk and Skogtiltaksfondet. The authors acknowledge the valuable contributions of Micky Allen, Simon Berg and Stephan Hoffmann to this work. The authors also thank the two anonymous reviewers for their constructive comments on an earlier version of this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Skogtiltaksfondet and Utviklingsfondet for Skogbruk.

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