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Pre-Commercial Thinning Increases the Profitability of Norway Spruce Monoculture and Supports Norway Spruce–Birch Mixture over Full Rotations

Mostarin Ara [1,*,†], Mattias Berglund [2], Nils Fahlvik [2], Ulf Johansson [3] and Urban Nilsson [1]

1 Southern Swedish Forest Research Centre, Swedish University of Agricultural Science, SE-23422 Lomma, Sweden; urban.nilsson@slu.se
2 Skogforsk, SE-26890 Ekebo, Sweden; mattias.berglund@skogforsk.se (M.B.); nils.fahlvik@skogforsk.se (N.F.)
3 Tönnersjöheden Experimental Forest, Swedish University of Agricultural Sciences, SE-31325 Simlångsdalen, Sweden; ulf.johansson@slu.se
* Correspondence: mostarin.ara@slu.se; Tel.: +46-0729420316
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Abstract: Pre-commercial thinning (PCT) is a common measure in Norway spruce (*Picea abies* L. Karst.) stands but the profitability of doing PCT and timing of PCT has not been fully investigated over a full rotation. Further, limited knowledge is available for mixed forest management compared to monocultures. In this study, different PCT strategies were tested to investigate the effect of PCT and timing of PCT on the production and profitability of Norway spruce monocultures and mixed Norway spruce–birch stands. A forest decision support system was used to simulate stand development during the whole rotation. Our study findings show that there is a positive effect of PCT on Norway spruce plantations' long-term profitability but that the timing of PCT has little effect on profitability. However, site variation might influence the effect of PCT timing on the profitability of Norway spruce stands. Moreover, we also found that retaining 1000 Norway spruce ha^{-1} and 1000 birch ha^{-1} after PCT supports a mixture of Norway spruce and birch over a full rotation, with little or no economic loss compared to pure Norway spruce stands. Therefore, such a mixture can lead to profitable production while still providing other ecosystem services.

Keywords: early PCT; late PCT; mixed forest; Norway spruce; pre-commercial thinning; stump sprouting

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1. Introduction

A forest management programme is a chain of different management practices. One essential part of this chain is managing the young stand. The success or failure of young stand management greatly influences future stand development and, subsequently, the combined profitability of all forest management treatments during a rotation. Regeneration with planting following clearcutting is one of the most frequently used forest-regeneration programmes in boreal and hemi-boreal forests [1]. Additional natural regeneration of conifers and broadleaved tree species is very common in planted stands in southern boreal forests in southern Sweden and often results in dense young forests. Norway spruce (*Picea abies* L.) is the most commonly planted species [2] in this region and natural regeneration of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) is often abundant [3,4]. Strong competition can be observed in these dense stands, which could lower individual trees' growth. Pre-commercial thinning (PCT) is used to release competition in young stands and even out the spacing between residual trees [5]. PCT generally increases individual trees' diameter growth [6–8] and provides an opportunity to select desired future tree species composition [9,10].

PCT is a widespread measure in young Scandinavian forests. Stand densities of 2000–2500 trees ha^{-1} are typically recommended after PCT in this region, with the specific density depending on soil fertility, stand age, and planned management during the rest of the rotation period [11,12]. Several studies found a positive relationship between the number of stems after PCT and volume growth [7,8,13–17]. Because of the importance of PCT on diameter increment, attention has been given to studying the influence of spacing after PCT on both individual trees and stand growth. The other important aspect is the timing of PCT (tree height at PCT), which influences tree growth dynamics, competition between primary and secondary crop trees, and stand development [18,19]. PCT is usually carried out when tree height is between 2–4 m. Early PCT (height lower than 2 m) is recommended to increase diameter increment [12,19,20]. Late PCT can improve external wood quality by reducing the branch diameter at the trunk [21,22]. However, early PCT enhances stump sprouting [23], which may reduce the production of crop trees [24,25]. In this case, a second PCT is sometimes needed, which increases the total PCT cost, especially as the time spent on PCT is positively correlated with tree's dimensions [26]. Despite the importance of PCT timing on the growth and profitability of forest management, it has received little research attention. PCT has a long-term impact on stand development and financial outcomes. Thus, an evaluation of different PCT strategies should cover the whole cycle, from PCT to final felling. Earlier studies considered full rotations in investigations on the effect of PCT timing on growth [6,19] and profitability [27] but only for Scots pine (*Pinus sylvestris* L.). To our knowledge, no studies have investigated the PCT-timing effect on Norway spruce during a full rotation. Moreover, no studies have considered the effect of stump sprout removal on the growth and profit of a stand during a full rotation. In this regard, a study of Norway spruce with different timing of PCT over a full rotation is of great value for practical forest management.

Traditionally, the natural regeneration of birch in Norway spruce plantations has often been considered an obstacle to conifer-oriented forest management and is usually totally removed during PCT. However, interest in mixed stands of conifers and broadleaves has increased in recent years and the use of the mixed forest is supported by governmental policies and forest certification systems. There is also a focus on ecosystem services other than timber production [28–33]. However, management of a mixed forest, for example, Norway spruce and birch, is a challenge because the species have different growth patterns. Birch grows faster at the beginning of the rotation and has an early culmination of growth, while Norway spruce has the opposite pattern. A mixture of Norway spruce and birch, with birch as a low shelter, may produce a higher total volume compared to monocultures of Norway spruce early in the cycle [34–36]. Birch shelter is typically removed in early to mid-rotation to promote the growth of Norway spruce. However, there are many possible reasons to keep some birch in stands throughout the rotation.

Few studies have aimed to investigate the possibility of supporting both species in the mixture over a full rotation [9,37–39]. Results indicate that volume production can be equal or slightly lower if some birch is retained during the whole rotation [9,39,40]. As PCT has the potential to change the species composition and structure of young forests [10], new management alternatives could be evaluated to support both species in the mixture. In this study, we investigate the effect of PCT timing on Norway spruce's growth and profitability during a full rotation period. Furthermore, we evaluate PCT strategies to support mixtures of Norway spruce and birch over a full rotation. To reach these goals, we address the following questions:

1. Does PCT increase the long-term production and profitability of Norway-spruce-dominated stands?
2. Does the timing of PCT affect the long-term production and profitability of Norway-spruce-dominated stands?
3. Do mixed Norway spruce birch stands reduce the yield and economic return compared to Norway spruce monocultures during a full rotation?

2. Materials and Methods

2.1. Field Experiments

Data from a pre-commercial-thinning experiment located in four fertile sites of southern Sweden were used in this study (Figure 1). The experiment was established between 2013 and 2014 in planted Norway spruce stands with admixed naturally regenerated birch. The stands had previously been used to study different PCT strategies and their effect on forage production and stand development [41]. An early PCT was conducted when Norway spruce was 1–2 m and birch was 2–2.5 m tall. Four PCT strategies were tested: 1. **Control**: no PCT, 2. **PCT-Total**: removing all natural regeneration, 3. **PCT-Spot:** removing all broadleaves with a 0.75 m radius of Norway spruce crop trees, and 4. **PCT-mix**: removing all broadleaves except 2000 birch ha^{-1} along with 2000 Norway spruce ha^{-1}. Three to six growing seasons after the first PCT, a second PCT was carried out in all sites. The aim was to create Norway-spruce–birch mixtures as well as to evaluate the long-term effect of PCT and timing of PCT on Norway spruce production and profitability. The earlier four strategies (in the first PCT) included in the previous study of forage production were divided into seven new strategies/treatments (Figure 2). The strategies were:

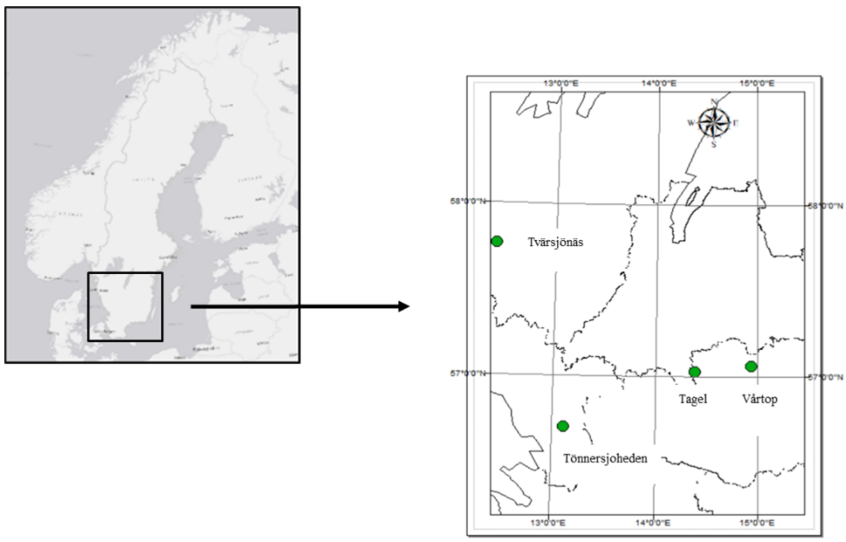

Figure 1. The pre-commercial-thinning experiment, located in four sites in southern Sweden. Each experimental site is marked with a green dot. The site index of Norway spruce (H100) varied between 32 and 34 depending on the site [42].

Control (CTR): half of the control treatment from the first PCT remained as an untreated control.

Late PCT (NS_LATE): in the other half of the control treatment, a PCT was performed (height of Norway spruce was 4.5–6 m) leaving 2000 Norway spruce ha^{-1}.

Early PCT (NS_EARLY): in half of the PCT-Total, stump sprouts were retained.

Early and Late PCT (NS_COMB): in the other half of PCT-Total, all stump sprouts were removed leaving a pure Norway spruce stand with 2000 stems ha^{-1}.

Mixed sparse (MIX_SPARSE): one-third of PCT-spot and PCT-mix were converted into a mixed forest with 500 Norway spruces and 500 birches ha^{-1}.

Mixed dense (MIX_DENSE): one-third of PCT-spot and PCT-mix were converted to a mixed forest with 1000 Norway spruces and 1000 birches ha^{-1}.

The remaining thirds of PCT-spot and PCT-mix were not used in this study.

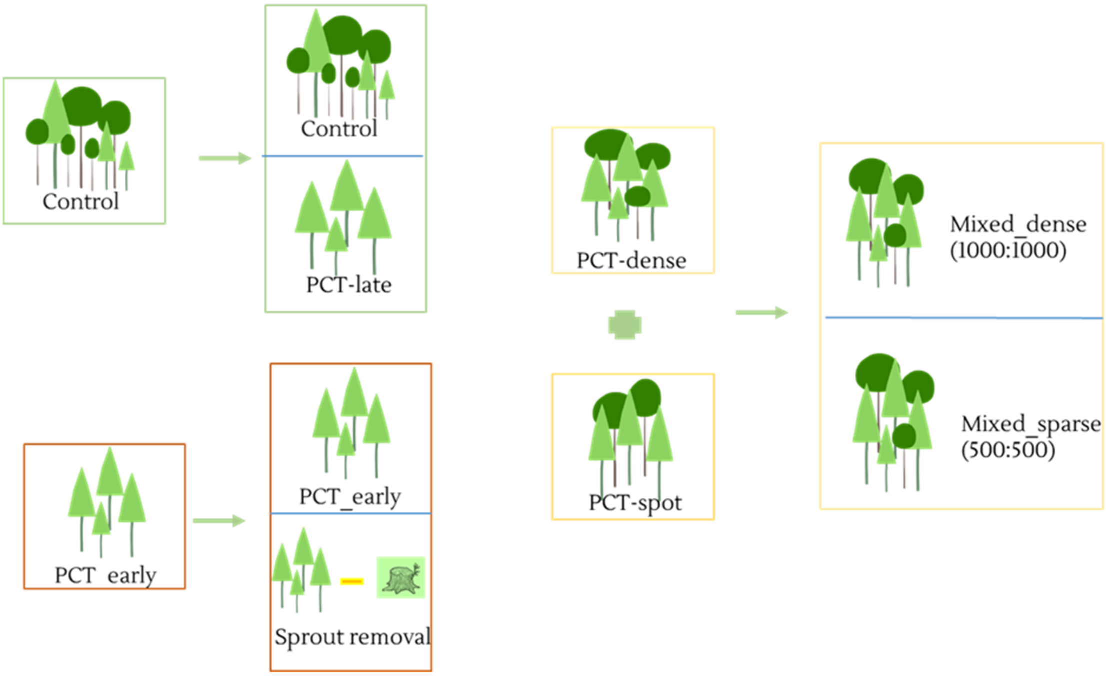

Figure 2. Treatments used in the 1st and 2nd pre-commercial thinnings. The same colour frame between 1st and 2nd PCT indicates that the new treatments in the 2nd PCT build on 1st PCT treatment.

2.2. Inventory

After the second PCT, each block (gross plot) consisted of various PCT treatments. Inside the gross plot, a net plot was placed where all the Norway spruce and birch trees were marked. The size of net plots varied between 0.0375 and 0.049 ha. The number of main stems was kept near 2000 trees ha^{-1} for all treatments except for mixed sparse (1000 trees ha^{-1}). All the marked stems were retained in the plots and the rest of the trees were removed. Diameter at breast height (DBH), damage, and tree species were recorded for all marked trees within the net sample plots. Height was measured on 20 sample trees of each species per plot.

2.3. Simulations

2.3.1. Growth

After the second PCT, stand development from the time of the latest inventory until the end of the rotation, including future thinnings and final felling, was simulated for each PCT strategy using Heureka forestry decision support system [43]. Heureka requires data about the site (e.g., latitude, site index, and vegetation type), the stand (age, management history), and the trees (tree species, diameter, and height). The single-tree data from the latest field inventory was used as input to Heureka. The Heureka system includes a large number of empirical models describing growth, mortality, and ingrowth [44,45]. Separate models were used to estimate the growth of the young and established stands in Heureka. Height growth was estimated in the young stand, whereas functions for basal area growth were used in the established stand. The transition between the two stages occurred at an average stand height of 6–7 m. Basal area development of the established stand was estimated with a combination of stand-wise and tree-wise growth models [45]. The stand-wise models determined the growth level, whereas the tree-wise models were used to distribute the growth among single trees [45]. The competition was described with the total basal area and with a distance–independent competition index including the basal area sum of trees larger than the subject tree. Stand development was estimated recursively in 5-year periods. We used PlanWise application to simulate the stand development which is included in Heureka system. PlanWise application is a system for analysing a large set of forest management options in order to identify the best alternative using optimisation based on user-defined objectives and constraints. This application includes few steps-data import, defined management strategies, treatment generation, defined goal and constraints, treatment selection, and results analyses.

2.3.2. Management Alternatives

Each management strategy (CTR, NS_EARLY, NS_LATE, NS_COMB, MIX_SPARSE, MIX_DENSE) within each site was represented by a single stand in Heureka. PlanWise includes a treatment program generator that computes a set of thinning and final felling alternatives for each stand unit within frames set by the user. The number and timing of thinnings and the timing of the final felling varied between the generated management alternatives. The initiation of thinnings was based on thinning guidelines incorporated in Heureka. The default thinning guideline was used, representing the guidelines provided by the National Forest Agency [46]. An understory cleaning was simulated for technical reasons before commercial thinning if the number of non-commercial stems (<7 cm DBH) exceeded 500 stem ha^{-1}. Minimum stand age at final felling according to the Swedish Forest Act was used as a restriction on the generation of management alternatives. Up to 100 alternatives were generated for each treatment and site.

2.3.3. Income and Costs

Heureka includes functions to distribute harvested wood among different commercial assortments. The default price list for Norway spruce in Heureka was used. The price list included two quality classes for Norway spruce. The pricing varied with the dimension of the logs (14–36 cm in top diameter). The default of 87% of timber logs assigned to class-1 and 13% to class-2 was used for all management alternatives. Separate simulations were carried out for two different assortments of birch, birch timber, and birch pulpwood. For the simulation, using birch timber assortment, all the logs greater than 14 cm in top diameter were assorted as timber and thinner trees were assorted as pulpwood. Diameters > 16 cm were graded as class-1 and diameters between 14–16 cm were graded as class-2 birch timber. During the simulation with birch pulpwood assortment, all logs irrespective of dimension were assorted as pulpwood. The prices for different assortments for Norway spruce and birch are found in Table 1.

Table 1. Price for the assortment of Norway spruce and birch.

Species	Assortment Price (EUR/m^3)		
	Timber		Pulp
	Class-1	Class-2	
Norway spruce	59	40	25
Birch	53	42	29

Felling costs were based on productivity norms for harvesters at thinning [47] and final felling [48] and for forwarding of round wood [49]. The forwarder and harvester costs at thinning and final felling are found in Table 2. The understory cleaning was assumed to cost EUR 800 ha^{-1} in CTR and 600 EUR ha^{-1} in NS_EARLY. Costs and incomes during a rotation were calculated by subtracting regeneration costs and cost for PCT from the economic output from thinnings and final felling generated in Heureka. Planting of Norway spruce was assumed to cost EUR 1200 ha^{-1}. Time consumption at PCT was based on time studies of motor-manual PCT [50]. The cost for motor-manual PCT was set to 33 EUR/h.

Table 2. Forwarder and harvester costs during thinnings and final felling.

Machine	Cost (EUR/h)	
	Thinning	**Final Felling**
Forwarder	66	75
Harvester	94	104

2.3.4. Economic Calculations

Land expectation value (LEV) was calculated according to Equation (1), where *R* is the net amount of PCT, thinning, or final felling; *c* is the net present value of regeneration costs; *t* is the time since last final felling (yr); *u* is rotation length (yr); and *r* is the interest rate.

$$LEV = \left(\sum_{t=0}^{u} R_t \times (1+r)^{-t} - c\right) \times \frac{(1+r)^u}{(1+r)^u - 1} \quad (1)$$

LEV was calculated for three different interest rates: 1, 2, and 3%. The reference year in the calculations of LEV was the year of final felling of the previous stand ($t = 0$ in Equation (1)) for all management alternatives. LEV for all the generated management alternatives in Heureka was compared and the alternative with the greatest LEV was selected for each management strategy and site. All the results were interpreted with a 2% interest rate and mean annual volume increment (MAI) was interpreted with a birch timber assortment. MAI included standing volume, the volume of dead trees since the simulation's start, and the volume of trees removed during commercial thinnings. The volume of trees removed during PCT was not included.

3. Results

Simulations of stand development over the whole rotation period showed that the number of thinnings and basal area development varied between treatments (Appendix A). The age of final felling differed among interest rates. Moreover, at the end of the rotation, Norway spruce was dominant in both Norway spruce monocultures and spruce–birch mixtures in terms of volume production. The effect of PCT timing on total volume production varied between sites, and volume production of MIX_DENSE was comparable with Norway spruce monocultures (Figure 3).

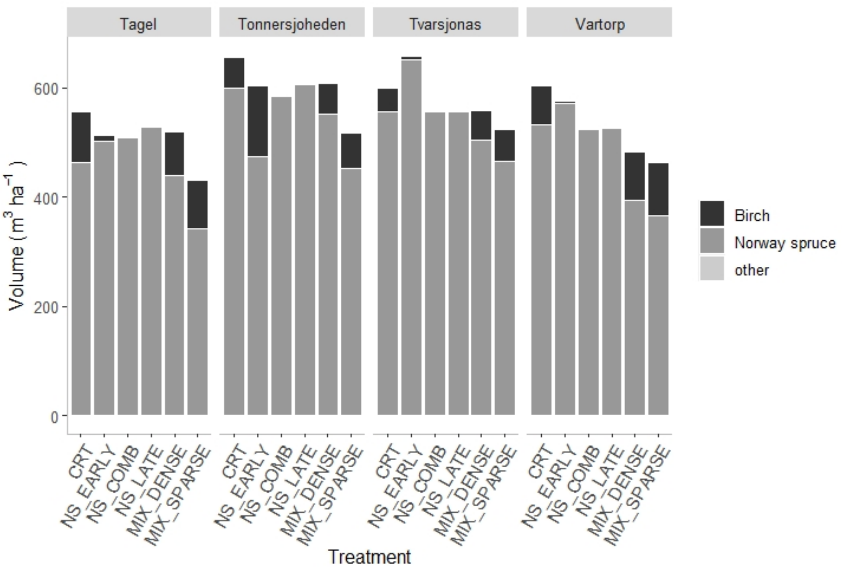

Figure 3. Standing volume of stands during final felling across multiple sites with different PCT strategies. The treatments were: control (CTR), early PCT (NS_EARLY), early and late PCT (NS_COMB), late PCT (NS_LATE), mixed sparse (MIX_SPARSE), and mixed dense (MIX_DENSE).

Depending on the site properties, there were both positive and negative effects of PCT on the MAI of Norway spruce stands. MAI in NS_EARLY was higher than NS_LATE in three out of four sites (lower only in Tönnersjöheden). In addition, MAI was always lower in NS_COMB compared to NS_EARLY but varied (lower or higher) between sites when compared with NS_LATE. However, the MAI of MIX_SPARSE was always lower than Norway spruce monocultures but the MAI of MIX_DENSE was only marginally lower than Norway spruce monocultures, except in Vartorp (Figure 4).

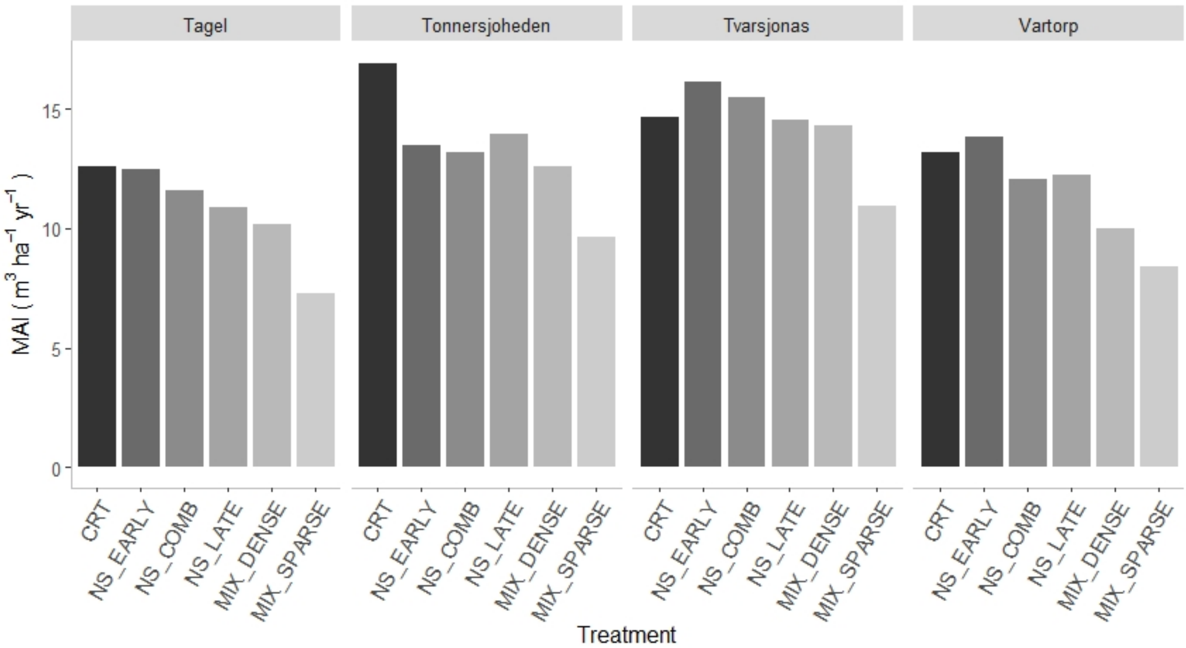

Figure 4. Mean annual increment (MAI) of stands during final felling across multiple sites and different PCT strategies. A 2% interest rate and "Birch pulpwood" assortment was used in the simulation. See Figure 3 legend for explanation of the treatments.

The income from thinnings was higher in PCT stands compared to no-PCT stands and there was also a trend for higher income in NS_LATE and NS_COMB compared to NS_EARLY. MIX_SPARSE always had a lower thinning income than Norway spruce monoculture. However, thinning income from MIX_DENSE was comparable with Norway spruce monocultures (Table 3).

Table 3. The total thinning income obtained from different PCT strategies across experimental sites. See Figure 3 for an explanation of the treatments. There was no thinning income in two sites of MIX_SPARSE stands which is indicated by NA in the table.

PCT_Treatments	Total Thinning Income (Euro ha^{-1})				
	Tönnersjöheden	Vartorp	Tagel	Tvarsjonas	Average
CRT	1032	959	1763	1978	1433
NS_EARLY	3230	1858	2585	3863	2882
NS_LATE	3621	5528	2964	6619	4683
NS_COMB	3117	5443	4639	6115	4829
MIX_SPARSE	1819	NA	NA	4451	1567
MIX_DENSE	3513	2961	2227	6729	3857

Overall, strategies, including PCT, had a positive effect on the LEV of Norway spruce over a full rotation at a 2% interest rate but the difference was minimal in Tönnersjöheden. Moreover, LEV was almost equal in NS_EARLY and NS_LATE in all of the sites, except in Tönnersjöheden. LEV was higher in NS_LATE compared to NS_EARLY in Tönnersjöheden.

Further, the effect of stump-sprout removal (NS_COMB compared to NS_EARLY) on LEV varied between sites and there was no common trend (Figure 5). In addition, there was always a lower LEV in MIX_SPARSE compared to Norway spruce monocultures. However, LEV of MIX_DENSE was higher than or almost equal to Norway spruce monocultures in three out of four sites and was lower than Norway spruce in the Vartorp site. However, the ranking of PCT treatments with respect to LEV was the same, irrespective of interest rate (Figure 5).

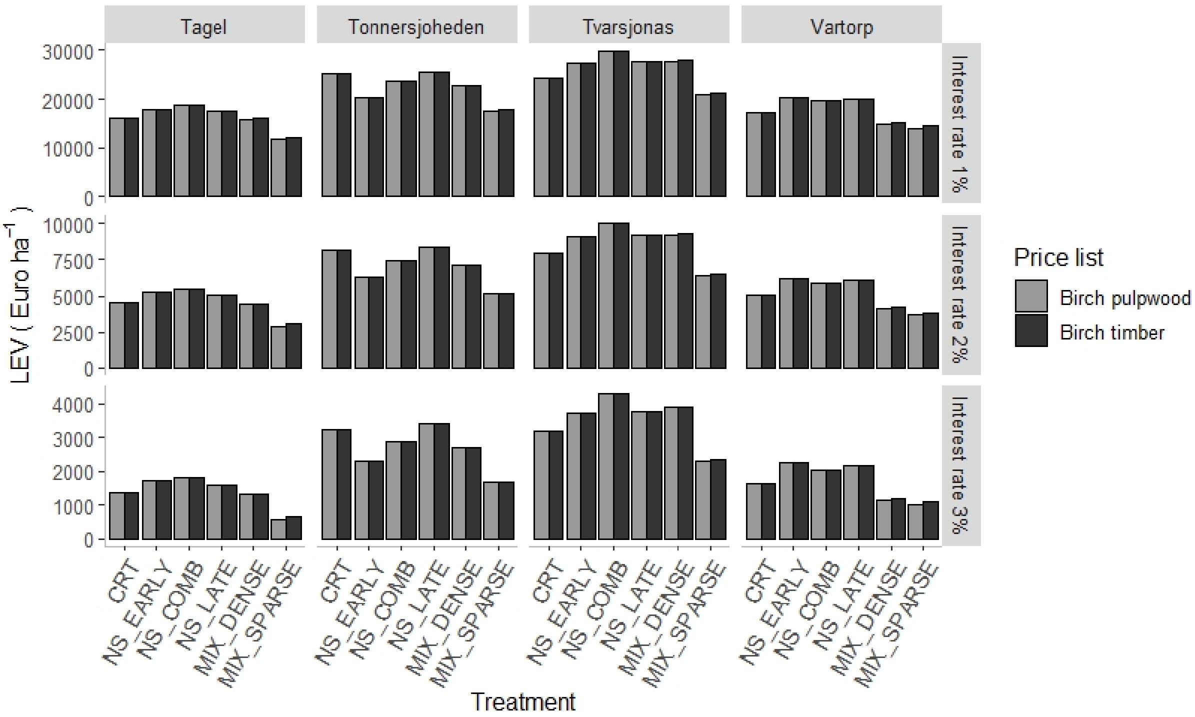

Figure 5. Land expectation value (LEV) of each stand at different sites, interest rates, and grading of birch logs after a full rotation. Here, logs greater than 14 cm in top diameter were assorted as timber and thinner trees were assorted as pulpwood (birch timber). All logs irrespective of dimension were assorted as pulpwood (birch pulpwood). See Figure 3 for an explanation of the treatments.

4. Discussion

4.1. Does PCT Increase the Production and Profitability of Norway Spruce?

Studies have shown that the individual diameter of remaining trees increases, whereas total volume production decreases with increasing removal at PCT [7]. The total volume growth is potentially greater in no-PCT stands than in stands with PCT [7,8,15]. In our study, we found both positive and negative effects of PCT on MAI but always a positive effect on profit. The profitability of PCT in planted Norway spruce stands is supported by earlier studies on other conifer species [51–53]. Moreover, along with our study, former studies of Scots pine also showed higher thinning income in PCT stands [6,19]. This indicates that PCT is an investment that pays back in the long run as well as in intermediate thinning operations. Based on our findings, PCT can be recommended in Norway spruce plantations in fertile sites for greater financial return in intermediate thinning and profit during the full rotation. The lower profitability of not doing PCT can be explained by the high understory cleaning cost (800 EUR ha^{-1}) connected with commercial thinning. It should be noted that the cost for understory cleaning was a fixed number based on assumptions and experience from practical forestry. The cost was not estimated based on the simulated stand structure. Moreover, no-PCT also reduced the diameter of harvested trees in commercial thinning, which resulted in higher costs for harvesting operations and reduced net thinning incomes. Further, the occurrence of birch in no-PCT stands could lower the profitability due to the smaller size and market value of birch.

4.2. Does the Timing of PCT Affect the Production and Profitability of Norway Spruce?

We found that the timing and number of PCTs had little effect on the profitability of Norway spruce in three out of four sites. However, earlier studies showed that early PCT is more economical than late PCT because of its lower cost [26] and higher growth benefit [54]. The minimal effect of PCT timing could be explained by the high understory cleaning cost of early PCT and higher income from commercial thinnings in late PCT. Further, the presence of stump sprouts in early PCT might negatively affect the growth of Norway spruce [25,55], which might reduce the profit. However, the higher profit in late PCT compared to early PCT in one site could be explained by the difference in site conditions between plots. The NS_LATE plot in the Tönnersjöheden site was on the lower part of a slope, whereas NS_EARLY and NS_COMB were higher up the slope, which may have contributed to the higher growth and profitability of NS_LATE.

Our research findings indicate that the timing and number of PCTs has little effect on the profitability of Norway spruce over a full rotation. Based on our findings, it can be recommended that forest owners can conduct PCT in Norway spruce stands in fertile sites at their convenience (early or late or stump-sprout removal), as long as PCT is conducted. However, it is hard to make concrete recommendations based on only one experimental study. More studies need to be conducted to reach solid conclusions and recommendations based on scientific results for practical implementation. However, the contradictory findings of our study (timing of PCT) compared to earlier studies on Scots pine (see Introduction) indicate that the effect of timing in PCT is not as straightforward as it was thought to be. It could vary depending on tree species, site fertility, and stand structure. However, these research findings provide guidelines for forest owners and managers regarding PCT and the effect of PCT on the profitability of Norway spruce stands during full rotations.

4.3. Do Norway Spruce–Birch Mixtures Lower the Yield and Economic Return Compared to Norway Spruce Monocultures over a Full Rotation?

In our case, MAI during a rotation was always lower in mixed stands compared to Norway spruce monocultures, which is supported by earlier studies [9]. This could be explained by the growth pattern of Norway spruce and birch and the lower yield capacity of naturally regenerated birch compared to Norway spruce on most site types. As a pioneer species, birch grows faster at an early age and then slows down relatively early, whereas shade-tolerant Norway spruce has an opposite growth pattern. Because of this difference in growth pattern, birch may play a complementary role in the growth of Norway spruce in young stands, resulting in high growth of Norway spruce birch mixtures [9,38,56]. However, at a later age, when Norway spruce starts to grow faster, competition rather than complementarity starts between Norway spruce and birch. This competition increases the self-thinning of birch, which could lower the MAI at the end of the rotation. Moreover, soil preparation, improved genetic material, and improved seedling types have resulted in increased growth of Norway spruce growth, while the growth of naturally regenerated birch has been little affected by silviculture. The relative growth of these two species may also depend on site fertility. The sites in this study were classified as fertile to very fertile, which could put Norway spruce at a growth advantage over birch.

We found lower MAI and LEV in MIX_SPARSE compared to MIX_DENSE. This is supported by earlier studies where there was lower production in sparse mixtures compared to dense ones [57,58]. However, in our case, it could be explained by the low density of Norway spruce in MIX_SPARSE stands. There were only 500 stems ha^{-1}, which could lower production and profit. In the MIX_DENSE treatment, 1000 stems of Norway spruce ha^{-1} had almost the same production and profit as monocultures with 2000 stems ha^{-1}. Pfister et al. (2007) [59] showed that wide spacing had little effect on the production of Norway spruce down to about 1000 stems per hectare.

The LEV of MIX_DENSE was comparable to Norway spruce monocultures, except at one site. The economic analysis of mixed forest was conducted using today's average birch timber price. The market for birch is small in Sweden and it may change in the future. This could change the economic value of the mixed forest. Moreover, the same regeneration cost was used for Norway spruce monoculture and mixed forest, but establishment costs can be reduced if the mixed forest is aimed at practical forest management [38]. Both of these factors could increase the LEV of mixed stands. However, other operational costs may affect the economic comparison between mixed stands and monocultures. Compared to Norway spruce monocultures, Norway-spruce–birch mixtures need a higher number of assortments, which can increase the cost of harvest [33] and could impact the profitability of mixed forests. This potential difference in costs was not included in our simulations.

Norway-spruce–birch mixtures provide a wide range of ecosystem services apart from timber production [33]. In comparison with Norway spruce monocultures, Norway-spruce–birch mixtures increase stand-level biodiversity [33]. There are also studies indicating an increased stand stability against wind damage [60,61]. A mixed forest can also function as a shield against biological agents [62,63] and provide cultural ecosystem services [35]. Further, young Norway-spruce–birch mixtures can provide forage for ungulates without production loss of Norway spruce [41]. It is not possible to translate all ecosystem services into monetary values and it was also not possible to incorporate all these benefits into the simulation system, for example, the benefit of resistance to pathogens, storm damage, etc. However, we found a small proportion of birch volume in the mixed forest at the end of the rotation and a recent study showed the density of birch is important in Norway-spruce–birch mixtures to maximise ecosystem services [55]. This needs to be kept in mind during the practical implementation of these research findings.

5. Conclusions

The simulation outcome indicated that PCT is an important economic tool in Norway spruce forest management but that the timing of PCT had little effect on the profit of Norway spruce. However, more studies need to be conducted to provide a solid recommendation. Moreover, keeping 1000 Norway spruce and 1000 birch ha^{-1} during PCT could be a potential mixture strategy to support both species in full rotation, which simultaneously supports profitability and a wide range of ecosystem services.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

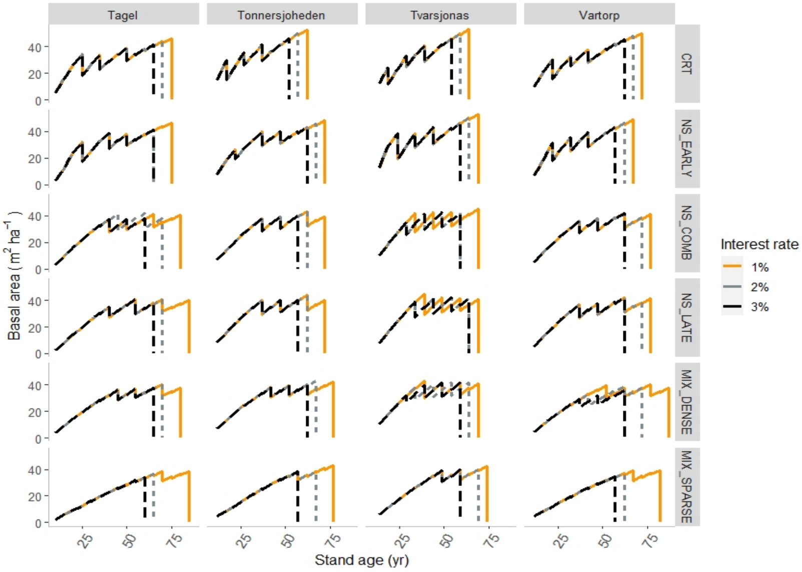

Figure A1. Basal area development of different PCT stands over time at different sites and interest rates. The "birch pulpwood" assortment was used in the simulation. See Figure 3 for an explanation of the PCT treatments.

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