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Pre-commercial thinning in Norway spruce-birch mixed stands can provide abundant forage for ungulates without losing volume production

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ABSTRACT

Mixed stands of Norway spruce and birch have the potential to simultaneously produce timber and provide large ungulates with a significant amount of forage during the regeneration phase. While the growth and yield of such mixtures are well studied, little is known about potential trade-offs between timber and forage production and which management techniques are suitable for meeting both goals. In this study, four different pre-commercial thinning (PCT) strategies were used to study the trade-offs between production and available forage for free-ranging ungulates in a Norway spruce-birch mixture. The four PCT strategies were: 1) retaining 2000 birch stems ha^{-1} with 2000 Norway spruce ha^{-1}, 2) removing all birches within a 0.75 m radius around Norway spruce stems, 3) removing all birches and other broadleaves, and 4) no PCT (control). Growth of Norway spruce was higher in the 2000 birch ha^{-1} and full removal treatments compared to the untreated control, but these two treatments did not differ from one another in volume production of Norway spruce. We found a negative effect of PCT on forage availability but no effect on ungulate browsing. Therefore, PCT strategies that provide both sufficient birch forage and maximize volume production of Norway spruce can be implemented.

1. Introduction

Regeneration after harvesting is the starting point for future stands in clear-cut forestry systems. In Scandinavian forests, clear cuts are most often regenerated with planted Norway spruce (*Picea abies* L. Karst.) or Scots pine (*Pinus sylvestris* L.), aiming for monocultures or mixed stands of these two native species (Ara et al., 2021; Bergquist et al., 2017). Natural regeneration of broadleaves, especially silver (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.) (Götmark et al., 2005; Karlsson et al. 2002) is often abundant on clear cuts due to soil preparation (Fries, 1985; Karlsson et al., 2002), sometimes resulting in more than 10,000 seedlings ha^{-1} (Holmström et al., 2016; Nilsson et al., 2002). Consequently, mixtures of conifers and birch are common in young forest stands in the Scandinavian countries. However, due to production-oriented forest management, birch and other broadleaves are often considered competitors to the planted conifer seedlings. Consequently, broadleaves are often removed during the pre-commercial thinning (PCT) or the first commercial thinning phase (Holmström et al., 2021).

Because birch is a pioneer species and Norway spruce is shade tolerant, birch can be used as a shelter over Norway spruce (Bergqvist, 1999; Klang & Ekö, 1999; Tham, 1994), thereby reducing the effect of spring frost on Norway spruce saplings. Birch is also an important source of forage for large ungulates, such as moose (*Alces alces*; Bergström et al., 1987; Bergqvist et al.,2014), roe deer (*Capreolus capreolus*; Bergman et al., 2005; Bergquist et al., 2009), red deer (*Cervus elaphus*; Miller et al., 1982) and fallow deer (*Dama dama*; Moore et al., 2000). Even though birch is not highly ranked in terms of food preference (Månsson et al., 2007), birch buds, leaves and twigs still represent a large part of the diet of these ungulates (Cederlund et al., 1980; Danell et al., 1985; Felton et al., 2020). Moreover, birch has a high capacity to tolerate browsing. Young birch trees can produce as much living biomass under moderate browsing pressure as they do in the absence of browsing, granted that the soil conditions are not too poor (Danell et al., 1985; Persson et al., 2005). Shoots of browsed birches can continue to produce desirable forage within browsing height for long periods (Danell et al., 1985).

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Because of the many benefits associated with birch, the maintenance of this resource is important during the development of new forest management practices. Mixed stands of Norway spruce and birch are well studied with the main emphasis on growth and yield in terms of specific species or total yield of the mixture (Frivold & Frank, 2002; Fahlvik et al., 2005; Johansson, 2001; Tham, 1994; Valkonen & Valsta, 2001) or using birch as a shelter-wood stand to reduce frost risk and thereby enhance the growth of Norway spruce (Bergqvist et al., 1999; Langvall & Löfvenius, 2002). Knowledge is more limited about the management of Norway spruce-birch mixtures as sources of forage for ungulates. In circumstances with high browsing pressure, forest management strategies that combine the production of both timber and ungulate forage would be of great value for production and ecological services. Early silvicultural treatment such as PCT can be used as a tool to handle the trade-off between timber and forage production, as PCT can regulate the mixture of the two tree species (Agestam, 2008; Fahlvik et al., 2015; Holmström et al., 2016).

Spot PCT (where competition is released within a certain radius of the Norway spruce crop trees (main stems)) can enhance the growth of Norway spruce, but as a large area in the stand remains undisturbed, it could still be a source of forage for ungulates. Previous studies showed the potential of spot PCT for competition release of conifer trees (Karlsson et al., 2002; Petterson & Fahlvik, 2007). Moreover, retaining the same amount of birch as Norway spruce in the stand could provide forage for ungulates without losing stand volume production. Studies have been done on different alternative PCT strategies regarding the trade-off between cost and production of conifer species (Fällman et al., 2003; Karlsson et al., 2002; Ligne et al., 2005) but to our knowledge, no studies have tested the effect of PCT strategies on the trade-off between volume production and forage for ungulates. Moreover, ungulates are highly selective in their browsing. They show a high preference for rowan (*Sorbus aucuparia* L.), aspen (*Populus tremula* L.), willow (*Salix* spp.), and oak (*Quercus robur* L.) (Månsson et al., 2007), a group of species we hereafter abbreviate as "RAWO". Ungulates browse more on these tree species than would be expected from their availability in their home range. Therefore, RAWO are considered disproportionately valuable in the integrated game and forest management. PCT can change the amount of RAWO in the forest, but there is a knowledge gap regarding their status after PCT in mixed Norway spruce and birch stands. In this study, we aimed to investigate the effect of PCT strategies on the availability of forage (birch and RAWO), and how it is utilized by browsing ungulates, along with Norway spruce volume production in southern Sweden. We answered the following questions:

1. How do different PCT strategies affect the height and volume growth of the retained crop trees of birch and Norway spruce?
2. How do PCT strategies affect ungulate browsing on birch and RAWO?

2. Materials and methods

2.1. Experimental sites, design, and PCT treatments

A pre-commercial thinning experiment established between 2013 and 2014 and located in three different sites of southern Sweden was used in this study (Fig. 1). After the final harvest, all sites were planted with Norway spruce, whereas birch and other broadleaves were naturally regenerated. At the time of PCT, the average height was between 1 and 2 m for Norway spruce and about 2–2.5 m for birch. The stand density varied between 10,000–40,000 stems ha^{-1} among experimental sites before PCT. In all sites, natural regeneration was dominated by birch. Moose and roe deer were common ungulates at all three study locations, while fallow deer may have occurred intermittently during the study period, but at low densities. Red deer were absent in the study sites (viltdata.se). Hunter-reported harvesting statistics (available at https://www.viltdata.se/) from years 2012–2016 indicate that the moose shot ranged between 3.5 and 4.1 individuals/km^2, and roe deer shot ranged between 7.2 and 9 individuals/km^2 among the experimental sites of our study (Appendix).

The experiment consisted of three PCT treatments and one control, distributed in a randomized block design, with one block per site (Fig. 2). The blocks were placed with minimal variation in site properties within the block. The treatment areas were between 0.5 and 0.8 ha. The treatments were:

- Control: No pre-commercial thinning. All the planted Norway spruce and naturally regenerated birch were retained.

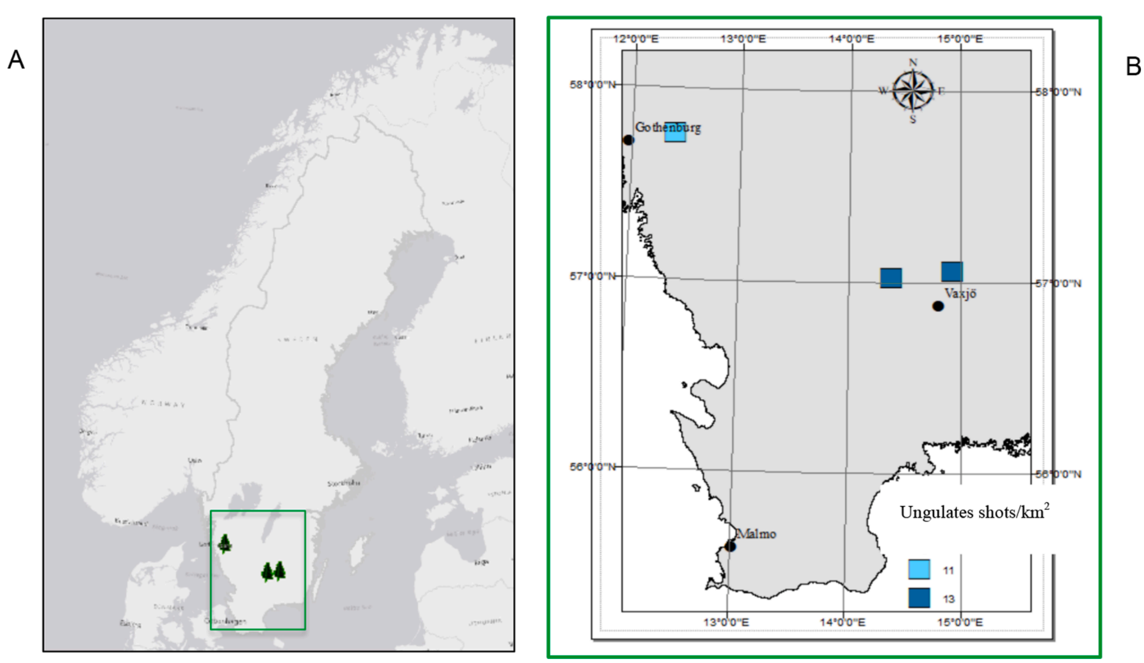

Fig. 1. Location of experimental sites in southern Sweden. In the left-hand figure, the Norway spruce symbol indicates the experimental locations. The filled square logo in the right-hand side figure indicates the same three experimental sites with ungulates shot/km^2 between 2012 and 2016 (moose, roe deer and fallow deer combined).

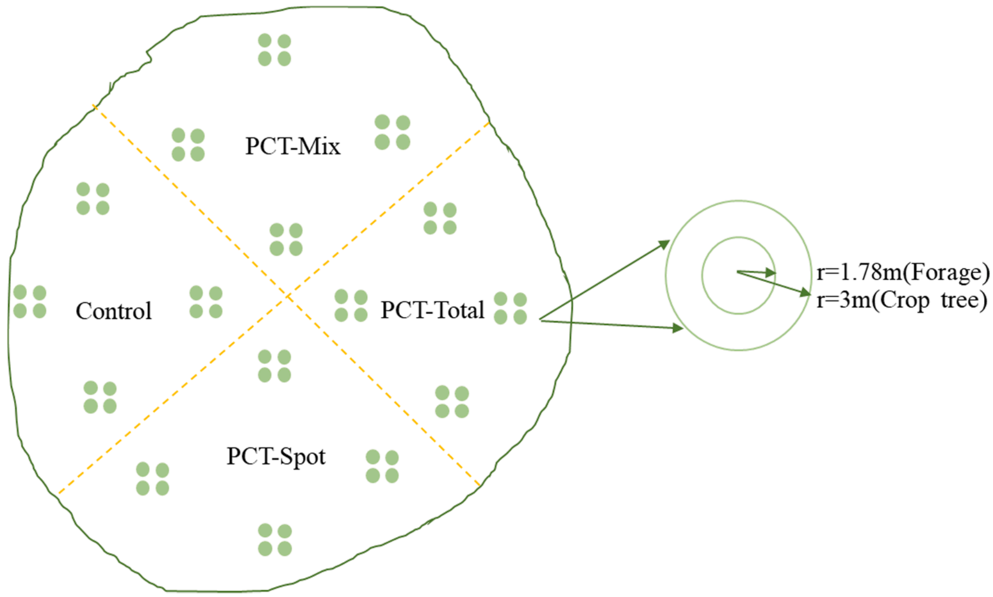

Fig. 2. Experimental layout for each site. Each green dot represents a plot center. The insert on the right shows one of four plots belonging to each cluster (4 clusters per treatment), where a small circular plot (1.78 m radius) was used for measuring forage, and a larger plot (3 m radius) was used for measuring the volume production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- PCT-Total (Total): All naturally regenerated broadleaves were removed. The total number of Norway spruce was 2000 trees ha^{-1}.
- PCT-Spot (Spot): All trees within a 0.75 m radius of each Norway spruce crop tree were removed. The density of Norway spruce was 2000 ha^{-1}.
- PCT-Mix (Mix): Naturally-regenerated broadleaves were removed except 2000 birches ha^{-1} that were retained along with 2000 Norway spruce ha^{-1}.

In each treatment area, four clusters were laid out in a systematic grid, and in each cluster, four sample plot centers were established for a total of 16 sample plots per treatment. All sample plot centers were used to estimate available forage in a smaller sample plot (1.78 m radius) and measurements of the future crop trees in a larger sample plot (3 m radius; Fig. 2). After PCT, there were 2000 Norway spruce ha^{-1} in all the treatments except in the control which had a higher number of Norway spruce due to dense planting and natural regeneration.

2.2. Inventory of crop trees and forage

Before PCT, all naturally-regenerated birch and planted Norway spruce were measured within the small sample plots. RAWO was present in all the stands but no inventory was done on RAWO before PCT. Moreover, species, height class (to the nearest 0.5 m), and diameter class (to the nearest 1 cm) were recorded in the inventory and height and diameter of trees were measured in the autumns of 2014, 2015, and 2016.

2.2.1. Crop-tree measurements

After the PCT, fixed number of crop trees (2000 trees ha^{-1}) were marked within the large sample plots with a unique identification. The crop trees were selected as the largest trees of birch and Norway spruce, respectively, in all treatments and in the control. The main stems were measured in height and diameter at breast height (1.3 m above ground) at the year of experiment establishment and after the 1st, 2nd' and 3rd growing seasons after PCT.

2.2.2. Inventory of birch, forage and browsed biomass

Three inventories were done to estimate the amount of birch branch and leaf biomass.

In the first step, all trees within the small sample plots were recorded to calculate total amount of branch and leaf biomass and evidence of browsing. Tree species, height class and browsing damage (top shoot browsing, side shoot browsing, and bent stems) were noted. Only recent browsing on birch (silver and downy) was recorded. No previous browsing was recorded. In addition, birch stump sprouts were measured from the first growing season after the PCT treatment. Tree species (silver or downy birch), the total number of sprouts, and height class were noted for each stump within the plot.

In the second step, browsing on birch was investigated within the large sample plots. Up to eight birches within each plot were randomly selected for detailed measurement. The height and diameter of the birches were measured. If there were signs of recent browsing, browsed branches were measured for detailed information: branch height, branch diameter, and bite diameter. Height and diameter measurements were collected every autumn, and browsing was recorded on these particular trees every second year.

In the third step, the browsing of stump sprouts was investigated within the large sample plot. Five birch stumps with sprouts within each large sample plot were marked in all PCT treatments except the control. Browsing on stump sprouts was first measured after the first growing season. If there was a recent bite on any of the stump's sprouts, up to five browsed sprouts were measured for detail information: the shoots' diameter, and for each fresh bite, the bite diameter (to the nearest mm) were noted.

2.3. Birch biomass and browsing calculation

We developed a biomass function using the destructive method to calculate the total available biomass for ungulates. Equations were developed separately for seed birch and young stump sprouts. Equations for seed birch were used for stump sprouts over three years old. Biomass sampling was done in all the height classes for seed birch, and biomass was estimated for leaves and branch wood (all branches included regardless of diameter). Biomass sampling was done in 2014, and additional measurements were done in 2017 and 2018. The green biomass was oven-dried, and the total dry weight was calculated by summing all the fractional dry weights. Biomass per hectare was estimated in two steps. First, destructive sampling was used to develop biomass functions with diameter and height as independent variables from harvested trees. These functions were applied to the birches measured in detail (up to eight per plot). From these birches, site-specific biomass functions were estimated with only height as an independent variable. The latter functions were then used for estimating per-hectare biomass of leaves and branches using height-measurements in the small plots.

A biomass model for stump sprouts was also developed using destructive sampling. In total, 48 birch sprouts were cut near sample plot centers from each treatment, except for the control (which had no stump sprouts). The sample sprouts were free from fresh browsing damage and other visible damage. The diameter and length of the branch were measured, and leaves were shaved off. After the measurement, materials were oven dried and weighted. Total dry weight (branches and leaves) was plotted against height to develop a regression model to predict the total biomass.

2.4. RAWO inventory

RAWO species were inventoried in each treatment annually if present. Total height was measured for trees taller than 30 cm and was considered as RAWO forage. Recent browsing was registered using the same protocol as for birch.

2.5. Data analysis

We estimated the volume of Norway spruce using single-tree equations developed by Brandel (1990) for trees with DBH > 5 cm and Andersson (1954) for trees with DBH < 4 cm. For all trees with a DBH between 4 and 5 cm, the two functions were used and averaged based on the relative distance of the DBH between 4 and 5 cm. We also investigated the volume growth of both species using data from the last two measurements. Individual tree stem volume growth was plotted against initial height class to investigate volume growth at different height classes and to compare treatments.

We used the developed biomass equation to estimate the total amount of biomass (branches and leaves) of seed birch and stump sprouts. We estimated the total biomass which is not the available forage for ungulates. The estimated biomass is the proxy forage and actual forage amount will be lower than the estimated biomass. The amount of browsed biomass was estimated by using functions of biomass of browsed diameters on the birches measured in detail. This gave an estimate of mean browsed biomass per site and measurement occasion for browsed birches. These mean values were used to estimate browsed biomass per hectare from the registered browsing damage on birches within the small sample plots.

For each PCT treatment where RAWO was present, we calculated the proportion of RAWO stems that had been browsed and their average height in different PCT treatments. As RAWO was not present in the PCT-Total and PCT-Mix treatments, data was only compared between control and PCT-Spot plots. We used ANOVA analysis to compare the variation of the target variables (volume production of Norway spruce and birch, volume growth, total biomass, browsed biomass) among treatments. In the analysis, PCT treatment was used as a fixed variable, and sites were used as a random variable. Finally, Tukey post-hoc analysis was used to assess the significance of differences between individual treatments. All the data and statistical analysis was done using R statistical software 4.0.3 (R core team, 2015).

3. Results

3.1. Volume, volume growth and height of crop trees

There was an overall significant positive effect of PCT on the volume of the Norway spruce crop trees after three growing seasons ($p = 0.003$).

Table 1
Tukey-derived p-value of pairwise treatment comparison to test significance of different stand characteristics of Norway spruce. Significant differences are highlighted with bold font. For description of PCT treatments see Fig. 3.

Variables	Treatment comparison					
	Total-Control	Spot-Control	Mix-Control	Spot-total	Mix-total	Mix-spot
Volume (dm^3/tree)	**0.005**	0.60	**0.01**	**0.03**	0.93	0.07
Height (m)	0.56	0.99	0.37	0.48	0.98	0.31
Volume growth (dm^3/tree/year)	**0.05**	0.80	0.06	0.15	0.99	0.19
Total birch biomass (MG/ha)	**0.01**	0.20	**0.02**	0.18	0.92	0.37

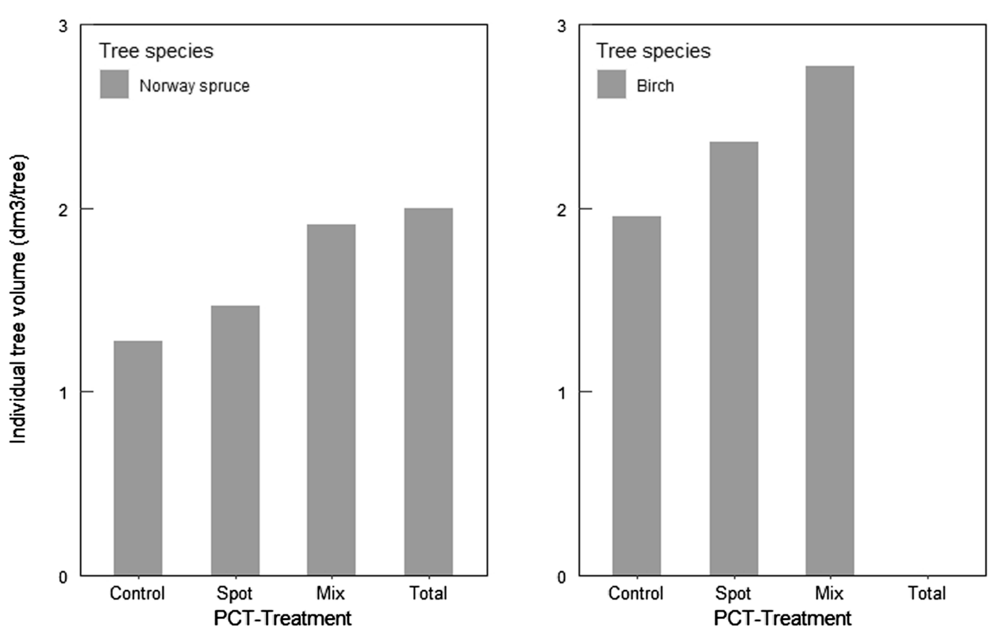

Fig. 3. Volume per tree of Norway spruce and birch for PCT treatments after three growing seasons. Significant differences ($p < 0.05$) between treatments within species are indicated with different letters. PCT treatments were Control (no PCT), PCT-Spot (Spot: all trees within a 0.75 m radius of the 2000 Norway spruce main stems were removed), PCT-Mix (Mix: all naturally-regenerated broadleaves were removed from this treatment except 2000 birches ha^{-1} that were retained along with the 2000 spruce ha^{-1}), and PCT-Total (Total: all naturally-regenerated broadleaves were removed).

However, there was no significant difference between PCT-Total and PCT-Mix, PCT-Spot and Control or PCT-Spot and PCT-Mix (Fig. 3; Table 1). There was no significant difference in volume of the birch crop trees when comparing PCT-Mix, PCT-Spot and Control ($p = 0.20$; Fig. 3; Table 1).

There was no significant effect of PCT treatment on the average height of Norway spruce and birch after three growing seasons ($p > 0.05$; Fig. 4; Table 1).

The volume growth response of the crop trees to PCT was similar in all height classes. PCT had a significant effect on the volume growth of Norway spruce ($p = 0.03$) but not for birch ($p = 0.47$). Norway spruce showed a significant difference between Control and PCT-Total, while PCT-Total and PCT-mix was nearly significant (Table 1; Fig. 5).

3.2. PCT, forage availability and browsing

After three growing seasons, total birch biomass ranged between 5 and 15 Mg ha^{-1} depending on different PCT treatments (Fig. 6A). PCT had a significant effect on the total birch biomass ($p = 0.01$). PCT reduced the total amount of birch biomass in the stands and there was a significant difference in birch biomass between control to PCT-mix and PCT-total. However, there was no significant difference in total birch biomass between the control and PCT-spot or between PCT-spot and PCT-total or PCT-mix (Table 1). Moreover, despite a relatively large amount of total branch and leaf biomass, only a small proportion was browsed during the three growing years of this study (Fig. 6B) and PCT had no clear effect on browsed biomass by ungulates ($p = 0.10$). The amount of total browsed biomass after three growing seasons was between approximately 40–60 kg/ha depending on the PCT treatment.

3.3. Occurrence and browsing of rowan, aspen, willow and oak (RAWO)

RAWO was found only in PCT-Spot and Control after PCT and its average height was 0.5 m. However, RAWO was present in every treatment before PCT. This means PCT reduced the RAWO forage availability between treatments. There were more than 3000 RAWO ha^{-1} in PCT-Spot and over 5000 RAWO ha^{-1} in the control but RAWO was intensively browsed in both of these treatments where it occurred (Table 2).

4. Discussion

4.1. Volume and height of crop trees

Overall we found a positive effect of PCT on the volume production of Norway spruce in early stages which is in agreement with earlier studies (Bataineh et al., 2013; Pettersson, 1992; Uotila & Saksa, 2014). Although released saplings of Norway spruce were substantially taller than in control stands, height growth was not significantly affected by PCT after three growing seasons. This is in line with earlier studies (Pitt & Lanteigne, 2008; Uotila & Saksa, 2014). It is well known that the diameter growth of northern conifers reacts to PCT 2–3 years earlier than height growth (Jobidon, 2000; Zenner, 2008). This could explain the lack of PCT effect on the height of Norway spruce. In this study, a PCT was done earlier than in typical forestry operations (when saplings were 2–3 m tall) which means earlier PCT can positively influence the stand volume. However, earlier PCT increases the risk of stump sprouting possibly making another PCT necessary at a later stage, which is expensive. Further studies need to be carried out to estimate cost efficiency and profitability of PCT strategies applied at early stages. Prior to more detailed recommendations being made, optimal timing needs to be determined as well. Also, we didn't find any difference in volume production of Norway spruce between PCT-total and PCT-Mix. This means keeping 2000 birch ha^{-1} along with 2000 Norway spruce ha^{-1} will not negatively affect the Norway spruce volume production. Although PCT-Total and PCT-Mix both had similar volume production of Norway spruce, PCT-Mix might have other benefits over PCT-total, for example mixed forest development and multiple forest services. Future stand development of the mixed stand (that was created during PCT) can help investigate the consequences of developing mixed forests in terms of production, profit and other services in comparison to Norway spruce monocultures.

4.2. PCT, forage availability and browsing

In general, PCT treatment reduced the total forage supply for the ungulates. All birches and RAWO were removed from PCT-Total treatment, and broadleaves were partially removed from the PCT-Mix and PCT-Spot treatments, which reduced the total forage (both birch and RAWO) for ungulates. However, by conducting PCT, we ended up having approximately 5000–15000 kg ha^{-1} of total biomass (birch leaves and branches) for ungulates after three growing seasons.

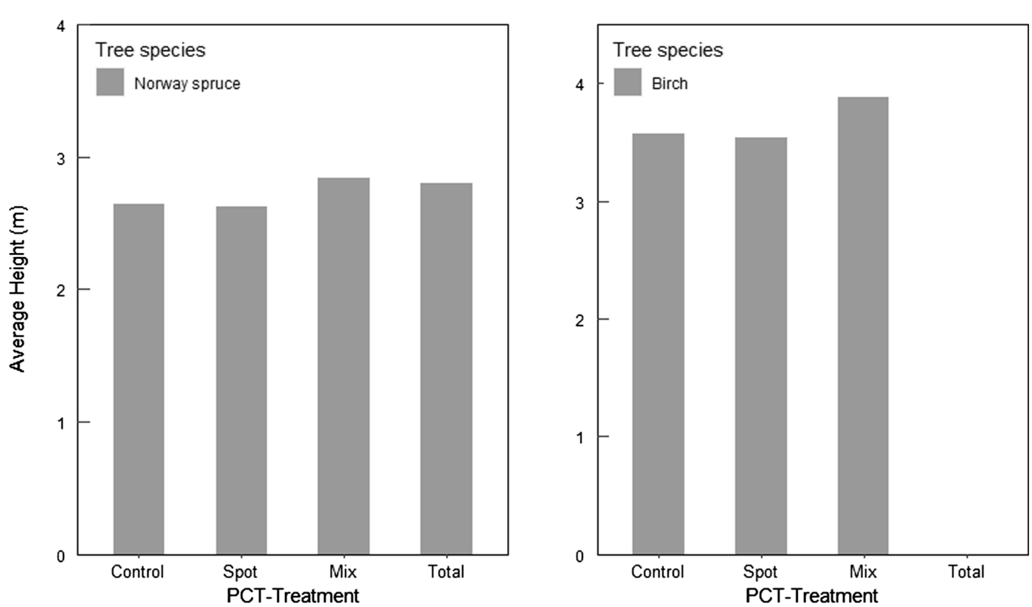

Fig. 4. The average height of Norway spruce and birch for PCT treatments after three growing seasons. For description of PCT treatments see Fig. 3.

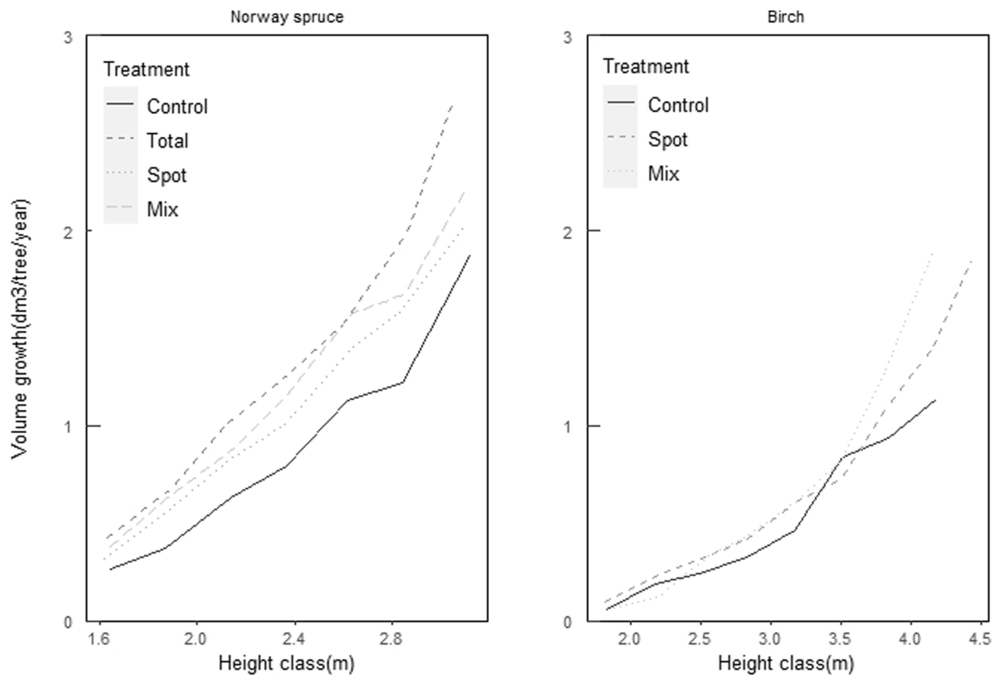

Fig. 5. Volume growth of Norway spruce and birch over initial height classes for different PCT treatments. For description of PCT treatments see Fig. 3.

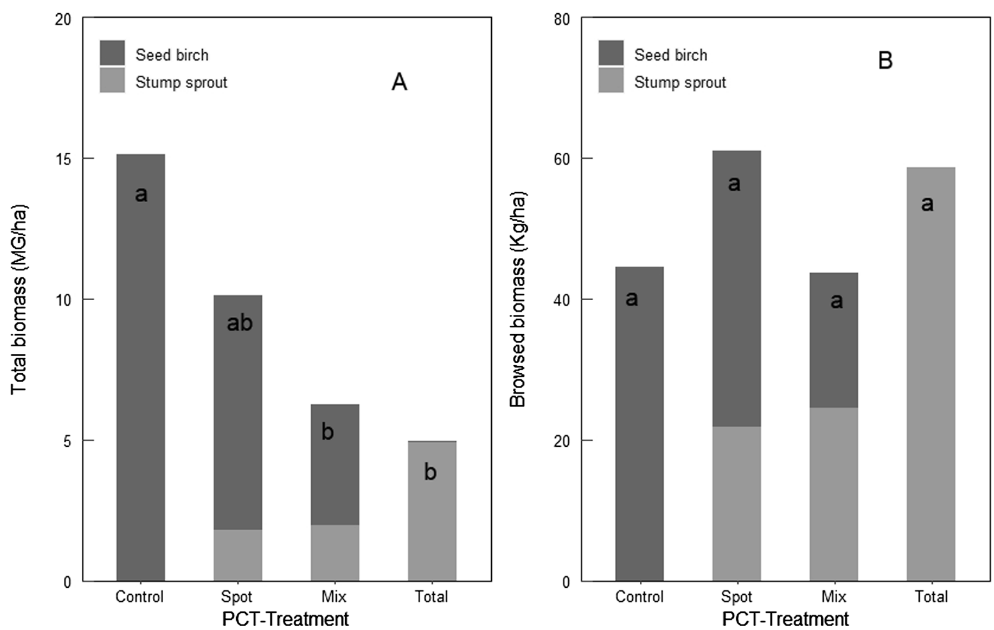

Fig. 6. Total birch biomass (seed birch and stump sprouts) in different pre-commercial thinning (PCT) treatments in the autumn of the third growing season after PCT (A) and total browsed biomass during the first three growing seasons after PCT (B). For description of the PCT treatments see Fig. 3.

However, the total biomass is the proxy forage and actual available forage is lower than the estimated amount. The browsed biomass was only a fraction of the total available birch biomass, and we did not see a significant difference among PCT methods in terms of the amount of birch browsed. A moose is expected to consume approximately 5 kg of dry plant matter per day during winter and about twice that much during summer (Persson et al., 2000). The amount we estimated that the ungulates had eaten from all available birch material in three growing seasons (ca. 60 kg dry matter ha^{-1}) suggests that an average hectare of PCT treated forest could have been utilized by one moose for about twelve days in winter time or six days in the summer. The degree of forage browsing was unexpectedly low, and several factors could explain this. First, for our research goal, we had to select Norway spruce and birch mixtures where Norway spruce was overtopped by birch, and birches were not heavily browsed. It was not easy to find suitable sites with such criteria, and it could be possible that to find such sites, we unintentionally ended up in sites with lower than average browsing pressure. Overall moose density could be lower in this region which could lower the browsing pressure (Helle et al., 1987; Nygren and Personen, 1993; Månsson et al., 2007; Bergqvist et al., 2014). Moreover, high abundance of birch in the landscape could be another reason for low utilization of this resource by ungulates (Wam & Hejljord, 2000; Hörnberg, 2001) in our study sites. Also, ungulates, especially moose, prefer to browse more attractive food if present. In our study sites, there

Table 2
Average height, number of stems per hectare and browsing proportion of RAWO (Rowan, Aspen, Willow and Oak). The proportion of browsing means the fraction of available branches and leaves that showed a sign of recent browsing during the three growing seasons. In the Total and Mix treatments, no RAWO was available to browse after PCT. For description of the PCT treatments see Fig. 3.

Treatment	Browsing proportion (%) RAWO	RAWO/ha	Average height (m)
Control	54.58	5007	0.5
Total	NA	NA	NA
Spot	48.16	3207	0.5
Mix	NA	NA	NA

were more than 3000 RAWO ha^{-1}, and about half of them had been browsed. This could lower browsing pressure on birch as RAWO is the most attractive food for ungulates (Månsson et al., 2007). However, we expected to see more browsing in the control plots because of higher biomass of available food. But this was not the case in our study after three growing seasons. Again, availability of RAWO may have reduced browsing on birch by drawing ungulates away from treatments that only had birch. In addition, crown height was higher in the control plots than in other PCT-treatments which reduced available food in this treatment during the end of the study period. Moreover, although we created relatively large areas for each treatment, the size of treatment areas was nevertheless much smaller than a moose's annual home range (Neumann, 2019) which could also influence why we did not see a clear effect of PCT method on the amount browsed.

4.3. RAWO development and limitation of the study

There were 3000–5000 RAWO ha^{-1} in the experimental sites and their average height was low compared to the mean height of Norway spruce and birch. With this difference in height, and considering the high browsing pressure on RAWO, it seems unlikely to get even a small admixture of mature RAWO trees in future stands in any of the sites. Similar effects of browsing and competition on the ecological function of RAWO trees have been found in other studies in Sweden (Angelstam et al., 2017). However, there was no inventory of RAWO before PCT and we found a negative effect of PCT on RAWO availability. This means we could not investigate how much RAWO was reduced due to PCT. Moreover, PCT-Spot is the only treatments that maintained RAWO. This treatment could be implemented if it is aimed to keep RAWO in this stands despite the loss of Norway spruce's volume production.

The primary aim of this study was to use PCT as a tool to create available forage for ungulates. Ungulates move freely and to test the effect of PCT, we had to use a relatively large area for each treatment. Because of this, we were unable to replicate the treatments within the same site. Moreover, the development of biomass equations based on only height can produce errors in biomass estimation as incorporation of height and DBH provides more precise estimation (Chave et al., 2014; Ketterings et al., 2001; Molto et al., 2014). Also, human error during sampling of total trees within sample plot could introduce errors in forage estimation at different years and treatments. Therefore, the absolute numbers of standing and browsed biomass only represent our best estimate but the difference between PCT treatments is more accurate since the same measurement procedures were used in all treatments.

4.4. Implementation in practical forestry

Boreal forests provide habitat to ungulates, which often are present at high densities and therefore can have negative effects on forest production and profitability (Edenius et al., 2002; Nilsson et al., 2016). It may not be practical to drastically lower just the number of ungulates considering their recreational and economic value. Instead, practical adaptive forest management may potentially reduce the problem without excluding ungulates. In this regard, availability of extra forage by conducting certain types of PCT in a Norway spruce-birch mixture might lower the overall browsing damage. However, despite our treatment blocks providing large amounts of biomass, very little was browsed. This could be very site specific and might be very different in sites with higher moose density. Moreover, we found a positive effect of PCT on Norway spruce volume production but a negative effect on forage availability. However, PCT had no effect on birch browsing by ungulates. In this case, PCT strategies that provide both sufficient birch forage and maximize volume production of Norway spruce (PCT-mix or PCT-total) can be implemented.

5. Conclusions

Pre-commercial thinning (PCT) positively influences the growth and production of young Norway spruce trees but negatively affects forage availability (birch and RAWO). However, PCT has no effect on birch browsing by ungulates. Therefore, certain PCT strategies (PCT-total or PCT-mix) can be used to maintain high volume production of Norway spruce while producing enough birch forage for ungulates. However, the PCT-Mix treatment may be a compromise between rapid growth of crop trees and future flexibility regarding possibilities for mixed-species stands.

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.

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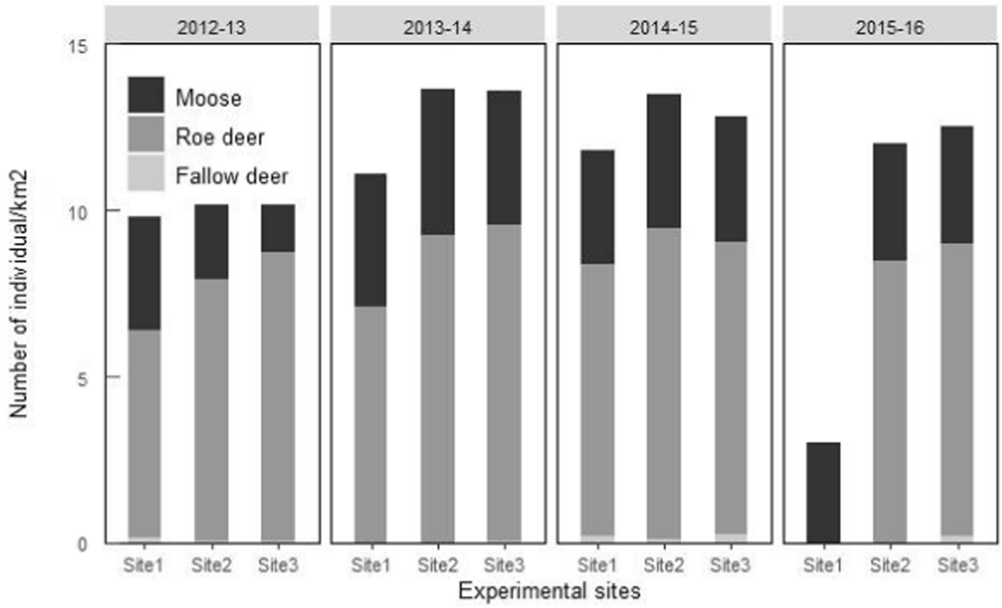
Appendix



Appendix 1. Number of different ungulates/km^2 shot in different years at the different experimental sites. Data is collected from viltdata.se.

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