forests

MDPI

Article

Effects of Increased Soil Scarification Intensity on Natural Regeneration of Scots Pine *Pinus sylvestris* L. and Birch *Betula* spp. L.

Mona Saursaunet, Karen Marie Mathisen * and Christina Skarpe

Department of Forestry and Wildlife Management, Faculty of Applied Ecology, Agricultural Sciences and Biotechnology, Inland Norway University of Applied Sciences, Pb 400, 2418 Elverum, Norway; monasaursaunet@gmail.com (M.S.); christina.skarpe@inn.no (C.S.)
* Correspondence: karen.mathisen@inn.no

Received: 22 February 2018; Accepted: 7 May 2018; Published: 11 May 2018

check for updates

Abstract: Achieving an optimal density of trees is essential for the final yield in commercial forestry. Soil scarification is commonly used in Scandinavia in order to produce successful regenerations of Scots pine (*Pinus sylvestris* L.), especially in areas with risk of browsing damage by moose (*Alces alces* L.). The research presented in this paper provides knowledge on how increased intensity of soil scarification affects the regeneration of pine and birch (*Betula* spp. L.). A total of 67 stands were treated with different intensities of soil scarification. Tree seedling density and current annual growth (CAG) were measured one to five years after scarification. Results showed that the density of pine and birch seedlings increased with soil scarification intensity. CAG of pine decreased with scarification intensity. CAG of downy birch decreased with proportion of exposed mineral soil, but increased with proportion of exposed humus. The effect of soil scarification intensity on CAG of both tree species was relatively weak. Results suggest that although increased scarification intensity had a positive effect on seedling establishment, the effect on early growth may be unfavourable. Further research is needed in order to evaluate the long-term effects of soil scarification intensity on growth.

Keywords: downy birch; silver birch; tree density; growth; moose browsing; mineral soil; humus; clear-cut; natural regeneration; regeneration of pine

1. Introduction

Moose (*Alces alces* L.) in Scandinavia forage on young Scots pine (*Pinus sylvestris* L.) during winter [1,2]. The establishment of young pine stands largely controls the forage availability for moose in areas where pine dominate in the moose winter diet [3]. In sites with heavy browsing pressure during winter, the regeneration of pine stands may be jeopardized by moose browsing [4,5], which causes substantial economic losses for foresters [6,7].

Many measures have been taken in order to reduce cervid browsing in young forest stands. Examples of damage reducing measures include fencing, the use of chemical repellents, and the use of aluminium tags fastened to the top of the tree seedling in order to block the moose from browsing [8]. Other studies focus on providing alternative forage for cervids in order to reduce browsing damage, such as introducing feeding stations with silage [9], making residues of branches and tree tops available after final logging and commercial thinning [2,10–12], or preserving trees of preferred browsing species within browsing height [13].

Dense forest stands produce much moose forage, and have a larger proportion of stems undamaged from moose browsing compared to sparser stands [4,14–16]. This is not only because of more moose forage being available in dense stands, but also because moose tend to rebrowse on the same trees repeatedly. Rebrowsing occurs for both boreal coniferous and deciduous tree species [5,17–19]. Rebrowsing may be related to structural changes in new shoots [20] and increased quality and nutrient availability in the new shoots [21,22], making the tree more palatable. Additionally, increased accessibility of forage due to reduced height development may favour rebrowsing. Consequently, in a dense stand, a proportionally small number of trees receives most of the browsing pressure until the stand mean height reaches above moose browsing height (approximately 5 m) [23]. Damaged trees, if not dead from browsing and competition, may then be removed later during the process of thinning, thus leaving a successful regeneration of trees to form the future stand.

Establishing dense stands may therefore increase the number of undamaged stems and reduce conflicts over browsing damage and moose population density. Soil scarification is a way of stimulating dense seedling establishments of pine and birch (*Betula* spp.), either by planting, sowing, or by natural regeneration [24–26]. In natural regeneration, the new stand regenerates from seeds spreading naturally from remaining seed trees after felling. Recommendations are to scarify the summer or the autumn before a good seed fall [27]. If a good seed fall occurs closely after soil scarification treatment, there would be less time for competing vegetation to establish in the scarification patches, which in turn would improve the germination of pine [25]. By further increasing the intensity of soil scarification, tree density may also increase [28].

Intensifying soil scarification may also have other beneficial effects on the stand. Soil scarification is shown to increase the growth of both pine [27,29] and birch [24,30]. This is mainly related to reduced competition with other vegetation, and elevated soil temperature during the growing season in the scarified patches [31,32]. Furthermore, moisture conditions in mineral soil are fairly stable due to capillary soil water capacity [33]. Of course, intensifying soil scarification has potential negative effects as well, such as nutrient leaching due to increased soil erosion [34] or frost heaving [35]. Scots pine is a light demanding species [36] and is therefore vulnerable to competition from other vegetation during early succession. The scarification procedure removes other vegetation, and thus reduces competition for light, nutrients, and water. The removal of other vegetation can also reduce the risk of damage caused by the release of Phytotoxins from dwarf-shrubs on pine and birch seedling development and growth [37,38]. The growth rate of trees may affect cervid browsing, as fast growing plants are generally more nutrient rich and thus more attractive for browsers [39,40]. Yet, fast growing trees may reach above browsing height at an earlier stage and thus reduce the time frame in which browsing may occur.

Soil scarification is a commonly used method in order to ensure successful tree regeneration, with widespread research spanning from, e.g., Japan [41] and the United States/Canada [42,43] to Europe [35,44]. Thus, our study questions have relevance beyond our study area in Southeastern Norway with clear applicability to other parts of the world. In commercial forestry in Norway, the common soil scarification practice is to expose mineral soil in 13–20% of the total area [26]. In order to establish even denser stands, foresters have suggested intensifying commercial soil scarification, which means exposing an even higher proportion of the mineral soil compared to what is normally done.

To evaluate whether high intensity gives the same positive effects as normal scarification, we have compared naturally regenerated pine stands treated with different intensities of soil scarification distributed along a gradient from low to high intensity in South-East Norway. As described earlier, knowledge on the effects of various levels of soil scarification intensity is highly relevant for modern forestry, and thus our study is an important contribution to the field. There is a general lack of studies on the effects of high soil scarification intensity on the regeneration of boreal forests. The few previous examples known to us mostly focus on comparing different methods of mechanical site preparation [28,31,35,45]. In our study, on the other hand, we investigated the effects of increased soil scarification intensity, and it is the only study known to us where this is measured as the proportion of exposed mineral soil and humus per surface area.

The dominating tree species in our study area were Scots pine, downy birch (*Betula pubescens* Ehrh.), and silver birch (*Betula pendula* Roth), and thus these were the focal species of our study. We predicted that the density of Scots pine and birch seedlings would increase with scarification intensity, as soil scarification is known to improve conditions for germination. We also expected time passed since soil scarification to increase seedling density, as more trees have time to establish. We expected that the effect of soil scarification intensity on growth would be weakest in the oldest stands, where the scarification patches probably would be more overgrown with competing vegetation. Further, we predicted that current annual growth (CAG) would increase with soil scarification intensity, as exposed mineral soil and humus provide favourable growth conditions in terms of soil water retention and soil temperature, and the removal of other vegetation reduces competition for light and water. We also expected CAG to increase with plant age, and logically for pine to be higher in areas with higher forest productivity, as the productivity indexes used in this study are based on the productivity of pine.

2. Materials and Methods

2.1. Study Area

The study area consists of three separate sites of roughly 50–60 km^2, each in Hedmark County in Southeastern Norway, at an altitude of 300–500 m above sea level. Two of these sites, Plassen and Ljørdalen, were located in Trysil municipality, and the third site, Gravberget, was located in Våler and Åsnes municipality. All sites are managed for commercial forestry. Ljørdalen and Gravberget consist of state-owned forests managed by the "State-owned Land and Forest Company" ("Statskog"). Plassen is managed by several private land owners and "Trysil Municipality Forest". Most of the stands included in this study were located in Gravberget (Table 1).

Table 1. Distribution of number of stands per study site and year of scarification.

Year	Gravberget	Plassen	Ljørdalen	Total
2011	0	9	0	9
2012	29	1	0	30
2013	15	1	4	20
2014	6	0	2	8
Total	50	11	6	67

The sites were located in the middle boreal vegetation zone, on podzolic soils, where boreal conifer forest and mixed conifer and deciduous forest constitute most of the natural landscape. Dominating tree species include Scots pine, silver birch, and downy birch, and to a lesser extent, Norway spruce (*Picea abies* (L.) H. Karst.), grey alder (*Alnus incana* (L.) Moench), rowan (*Sorbus aucuparia* L.), goat willow (*Salix caprea* L.), and aspen (*Populus tremula* L.) [46]. The field layer mainly consists of bilberry (*Vaccinium myrtillus* L.) and other Ericaceous dwarf shrubs. *Sphagnum* spp. L. mosses dominate the wettest parts of the bogs in the area, while heather (*Calluna vulgaris* (L.) Hull) and other dwarf shrubs can be found in drier spots scattered across the bogs. Average yearly precipitation during the last ten years (2005–2015) recorded from Trysil weather station was approximately 800 mm. Average temperature during the growing season (May–September) was +11 °C [47]. Growing season is defined here as the period with an average daily temperature above +5 °C [46].

2.2. Soil Scarification Treatment

Experimental stands (areas for forest treatment, usually between 0.2 and 1.3 ha) were distributed on a gradient from low to high scarification intensity. The study included 67 stands, all of which were treated with different intensities of soil scarification. Soil scarification intensity was defined here as the proportion of exposed mineral soil and proportion of exposed humus per surface area of a stand.

The scarification treatment was carried out using a forwarder equipped with a scarification attachment that would scrape under the lower part of the humus layer and lift it up and turn it over in order to expose the top of the mineral soil underneath. Soil scarification was carried out one to two years after clear cut logging, thus leaving the logging residues time to dry up after logging so that remains did not block the machine. Scarification treatments for this project have been carried out in Plassen since 2011, in Gravberget since 2012, and in Ljørdalen since 2013 (Table 1).

2.3. Field Procedures

For most of the 67 stands included in this study, ten sampling points with a fixed distance between each point were established on a straight line following the longest axis of the stand. The fixed distance between the sampling points was, depending on the size and the shape of the stand, 100 m, 50 m, or 25 m, in order to cover the area of each stand. If the shape of the stand did not allow ten points to fit on the same line, a perpendicular line was positioned at the longest perpendicular axis of the stand, or a parallel transect was added. In the 10 smallest stands, the number of sampling points was reduced to five to seven. A compass was used for direction, and the distance between sampling points was measured using a Global Positioning System (GPS) handheld device. At each sampling point, seedling density and current annual growth were measured in eight plots of 1 m^2. The plots were grouped into pairs of two in each cardinal direction (north, east, south, and west), 5 m from the point. All measures of seedlings were carried out at the end of the growing season, from early August to the beginning of October in 2015.

In each plot of 1 m^2, we estimated by eye the proportion of exposed mineral soil, the proportion of exposed humus, and "other cover" as a percentage of the surface area inside the plot. The relative proportions of exposed mineral soil and humus were used as measures of soil scarification intensity. Areas where pine could not establish, such as large rocks, tree trunks, or water bodies covering the whole or part of the plots, were registered as the proportion of "other cover". The remaining parts of the plots, which were not defined as either exposed mineral soil, humus, or "other cover", were mainly intact vegetation cover consisting of graminoids, mosses, lichens, and dwarf-shrubs. We counted and measured all tree seedlings inside the sampling plots and classified them to species. The species present were Scots pine, Norway spruce, juniper (*Juniperus communis* L.), downy birch, silver birch, rowan, aspen, and willows (*Salix* spp. L.). The total number of counts of each species can be found in Table 2. However, Scots pine and birch accounted for 98.3% of all observations. Therefore, the analyses concentrated on these species.

Table 2. Overview of counts per species presented with English and Latin names. The counts represent the sample size for each tree species.

Species	*Latin Name*	Counts
Scots pine	*Pinus sylvestris*	3084
Downy birch	*Betula pubescens*	7358
Silver birch	*Betula pendula*	666
Young unspecified birch	*Betula* spp.	4312
Norway spruce	*Picea abies*	170
Common juniper	*Juniperus communis*	1
Willows	*Salix* spp.	56
Aspen	*Populus tremula*	16
Rowan	*Sorbus aucuparia*	27
Total		15,690

For birch seedlings which were less than a couple of centimetres long, species identification was often difficult as species specific traits were not yet developed enough to be seen with the naked eye. Thus, these observations were recorded as undefined birch species. The age of the trees was measured by counting annual growth nodes. For pine and spruce, age determination was done by counting the number of shoot-whorls on the stem. Side branches normally start to develop during the third year [48]. Each shoot-whorl corresponds to one year of growth, for trees $\geq$ 3 years. Conifer tree seedlings of two years were distinguished from those which were $\leq$1 year by the presence of a fresher and greener shoot at the top of the seedling, and for pine, also by the presence of the longer double-joint needles [48]. For deciduous tree seedlings, age was determined from colour and/or growth form. Each node on the stem with a visible shift in coloration, or a ring-like scar, was counted as one year. Two-year-old deciduous trees were distinguished from one-year-olds by a woodier stem.

As a measure of current annual growth (CAG), length of the current year's top shoot was measured from the last shoot-whorl, for conifer trees, or last node for deciduous trees, on the stem to the base of the bud at the tip of the terminal shoot. For each stand, the following were registered: a unique identification number, study area site (Gravberget/Ljørdalen/Plassen), year of scarification treatment, scarification intensity, and forest productivity index. This index was based on the H40-system and was retrieved from forestry management plans. The classification of the H40-system describes the mean height for the ten trees per 1000 m^2, with the largest diameter at 40 years old at 1.3 m above the ground [49]. We registered four stands within productivity class F8, 36 within class F11, 26 within class F14, and one within class F17 (see supplementary materials). As there was only one stand within class F17, this class was merged with F14. The index was treated as a categorical variable, with levels F8, F11, and F14/F17, ranging from low to medium-low to medium-high productivity. High productivity index stands were absent from the study.

We observed little cervid browsing when sampling the data. This was expected as the stands were quite young and the mean height of the oldest stands was accordingly low (7.4 cm $\pm$ SD 7.7 cm for Scots pine, 11.2 cm $\pm$ SD 12.3 cm for downy birch and 26.2 cm $\pm$ SD 19.1 cm for silver birch, measured for seedlings > 2 growing seasons old). Browsing from cervids in these pine stands will likely increase when the mean height of the stands increases further with time. At this point, it is too early to evaluate the relationship between cervid browsing and soil scarification intensity, and hence we did not look further into this aspect.

2.4. Statistical Analyses

2.4.1. Data Exploration

Prior to statistical analyses, the data were checked for normality, homoscedasticity, collinearity, and outliers following the protocol explained in Zuur et al. [50]. Correlations between explanatory variables and the response variables were explored using pair plots, showing multi-panel scatterplots and corresponding Pearson correlation coefficients. The pair plots' function revealed which predictor variables were the most important ones, and these were the focus in the model selection process.

Proportion of exposed mineral soil and proportion of exposed humus were expected to be correlated as both are measures of scarification intensity. The spatial scale on the sampling point and plot level, however, is quite small, and the proportion of exposed mineral soil and proportion of exposed humus were not correlated: on sampling point level: $r = 0.25$, $p < 0.001$, and on plot-level: $r = 0.03$, $p = 0.019$. Since the correlation coefficient was low, we included both variables' proportion of exposed mineral soil and proportion of exposed humus as explanatory variables in the same models. On the other hand, the correlation between scarification year and age of seedling was somewhat high, $r = -0.44$, $p < 2.2 \times 10^{-16}$, so these two variables were therefore not included in the same models.

As scarification treatments were established in 2011, 2012, 2013, and 2014, the age classes of trees represented in our data range from one to five years. For downy birch, there was only one observation with age = 5, and for silver birch, there were only two observations with age = 5, hence these age classes were removed from the dataset due to too little data to carry out the analysis. For silver birch, there was only one observation in scarification year 2014, so this observation was also removed from the analysis.

2.4.2. Model Selection

We used mixed effects linear models to investigate the relationship between our measures of intensity of soil scarification and the response variables' seedling density and growth. We included random intercept effects in order to deal with the spatial dependency induced by the spatially nested sampling design. Model selection was done separately for the random model structure and the fixed model structure, following the model selection protocol for mixed effects models explained by Zuur et al. [51]. Akaike Information Criterion (AIC) was used as selection criteria. The model with the lowest AIC score was considered to be the most optimal model, and all models within ΔAIC = 2.0 were considered to be equally good [52]. If several models had equally low AIC values, the simplest model with the fewest parameters was presented, based on the principle of parsimony. All analyses were carried out in R 3.2.4 [53].

1. Seedling Density—Scarification Intensity

We used the number of trees per sampling point (8 m^2) as a response variable when modelling seedling density. We calculated the average of the eight plots per point for all numerical predictor variables (proportion of exposed mineral soil, proportion of exposed humus, and proportion of other cover), and used the average in the model for seedling density. We used sampling point (n = 626) as the spatial unit for tree seedling density instead of sampling plot, as there were excessively many zero-counts of trees on the plot level, which caused substantial overdispersion in the data. Model selection procedures were carried out separately for Scots pine and birch (both downy birch and silver birch combined).

We fitted generalized linear mixed candidate models specified with a negative binomial distribution with log link, using the glmer.nb function from the R package "lme4" [54]. The full model, (density ~mineral soil + humus + other cover + year of scarification + forest productivity), was combined with different combinations of random intercepts. The different combinations of random intercepts were comprised of the nested spatial levels: site, stand, and point. The random structure with the lowest AIC was included in the next step of model selection, which was identifying the most optimal fixed model structure [51].

A total of 24 candidate models based on our predictions for pine seedling density were compared using AIC. The full model with all possible predictor variables and interaction effects, and the full model minus the interactions effects, were included in the model selection for both pine and birch seedling density. We also compared all possible combinations of the focus variables' proportion of exposed mineral soil and humus, the most important variables from data exploration, and the predictor variable proportion of other cover. Proportion of other cover was included in order to take account of the proportion of the plots which were unsuitable for germination and thus had no density of tree seedlings. The most important predictor variables from data exploration for Scots pine seedling density were scarification year, proportion of exposed mineral soil, and an interaction effect between proportion of exposed mineral soil and scarification year.

In total, we compared 17 candidate models for birch seedling density with AIC, using the same method as described for pine. None of our predictor variables seemed particularly important for birch seedling density during data exploration. Hence, we chose predictor variables based on our initial hypothesis in order to create candidate models for birch seedling density. For birch, we compared all possible combinations of the focus variables' and the predictor variables' scarification year and other cover. Site productivity index was not included as this index was related to pine productivity.

The best model for seedling density from AIC selection was then validated by checking for overdispersion and by inspecting the normalized residuals in a "residuals vs. fitted" plot.

2. Current Annual Growth—Scarification Intensity

Current annual growth (CAG) was used as the response variable. The model selection procedure was done separately for Scots pine (n = 2803), downy birch (n = 6964) and silver birch (n = 572). Observations of small birch seedlings that did not show visible species-specific traits out in the field were not included in the CAG analyses. Downy birch and silver birch seemed to have different growth responses, hence we analysed the two species separately. We fitted a linear mixed effect model using the lme function in the R package "nlme" [55]. The full model, (CAG ~mineral soil + humus + other cover + year of scarification/age of seedling + forest productivity), was combined with different combinations of random intercepts. This was done for two variations of the full model; one including year of scarification and one including seedling age. The different combinations of random intercepts were comprised of the nested spatial levels: site, stand, point, and plot. The random structure with the lowest AIC was included in the next step of model selection, which was identifying the most optimal fixed model structure.

As the age distribution of trees, and thus also CAG, was non-normally distributed, we log-transformed CAG using the natural logarithm. Since we were mainly interested in the effects of soil scarification intensity on CAG, we only included observations of trees that established after the soil scarification treatment took place in the respective stand, i.e., had an age similar to or younger than the scarification treatment itself.

We compared 38 candidate models for pine CAG, 31 for downy birch CAG, and 15 for silver birch CAG. The full model with all possible predictor variables and interaction effects was included in the model selection for all pine downy birch and silver birch CAG. We also compared the full model without the interaction effects. The rest of the candidate models were all possible combinations of the focus variables' proportion of exposed mineral soil and humus, and the most important predictor variables from data exploration. This included age of seedling for all tree species, and certain interaction effects between the focus variables and the categorical variables (age of seedling, forest productivity and scarification year). For pine CAG, we compared the interaction effects between age and mineral soil, age and humus, year and mineral soil, year and humus, and forest productivity and mineral soil. For downy birch, we compared the interaction effects between age and mineral soil, age and humus, year and mineral soil, and forest productivity and mineral soil. For silver birch, we compared the interaction effects between age and mineral soil, age and humus, and year and humus.

The final model from AIC selection was fitted with restricted maximum likelihood and then validated by inspecting the normality of the residuals in quantile-quantile plots and residual histograms, and by confirming homoscedasticity in "residuals vs. fitted" plots.

3. Results

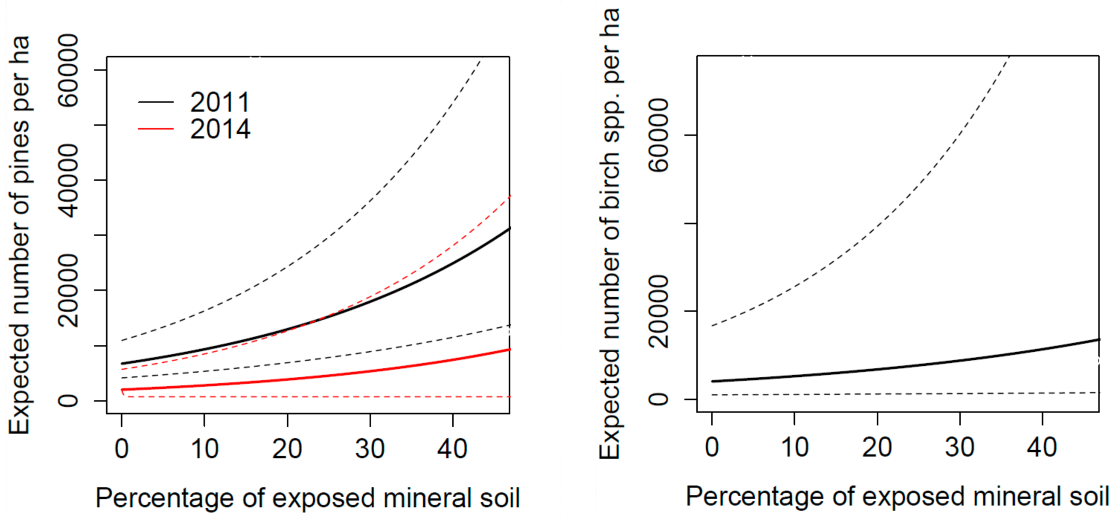
3.1. Tree Seedling Density

The highest proportion of exposed mineral soil/humus achieved in this study was 25%/27% on stand level, 53%/43% on the point level, and 99%/100% on the plot level. Pine seedling density increased with increasing proportion of exposed mineral soil and years since scarification (Table 3). The variation in density increased with increasing proportion of exposed mineral soil (Figure 1a). Expected density of pine seedlings at a level of 15% exposed mineral soil at point level was estimated as 10,991 pines per hectare (95% CI, 6065–17,235 per hectare), using the oldest scarification year (2011) as the baseline, and keeping the proportion of "other cover" constant at the average level of 8.7%. In comparison, expected density of pine seedlings at a level of 40% exposed mineral soil was estimated as 24,930 pines per hectare (95% CI, 11,497–54,056 per hectare). Pine seedling density decreased with increasing proportion of other cover.

Birch seedling density increased with increasing proportion of exposed mineral soil and proportion of other cover, the latter as opposed to pine seedling density (Table 3). The variation in density increased with increasing proportion of exposed mineral soil (Figure 1b). Expected density of birch seedlings at 15% exposed mineral soil was estimated from the model to be 5943 birches per hectare (95% CI, 1114–31,706 per hectare), for an average level of 8.7% other cover. Expected density of birch seedlings at 40% exposed mineral soil was estimated as 11 337 birches per hectare (95% CI, 1390–92,479 per hectare). It should be noted that there was a very large variation in birch density among different stands and sites, which was reflected by the large standard errors, and by the variance of the random intercept (stand nested with site), which was 1.16. By comparison, the variance of the random intercept (stand) for the pine density model was 0.26.

For pine seedling density, two candidate models had equally low AIC values (Table 4). We chose the simpler model as the most optimal one (pseudo-R-squared adjusted for the effect of the random model structure = 0.64). This one differed from the second-best candidate model by the exclusion of the interaction effect with scarification year and proportion of mineral soil. Proportion of humus was not important in either of the two best candidate models.

For birch seedling density, four candidate models had equally low AIC values (Table 4). We chose the simpler one as the most optimal model. This model only included the predictor variables' proportion of mineral soil and proportion of other cover (pseudo-R-squared adjusted for the effect of the random model structure = 0.48).



(**a**) (**b**)

Figure 1. Predicted model for expected density of (**a**) Scots pine seedlings and (**b**) birch seedlings (downy birch and silver birch combined) with increasing proportion of exposed mineral soil, and an average level of 8.7% "other cover". For pine, expected density is shown for stands scarified in 2011 (black solid line) and stands scarified in 2014 (red solid line). The dotted lines illustrate the 95% confidence intervals. Prediction lines for stands scarified in 2012/2013 were not included in this figure in order to maintain readability. For birch, scarification year was not included in the best model, and is therefore not included in the figure.

Table 3. Final model parameters with corresponding estimates and standard errors (SE) for Scots pine and birch seedling density fitted as Generalized Linear Mixed Models (GLMMs) with negative binomial error distribution. Stand was included as a random intercept for the pine model, and stand nested within site was included as a random intercept for the birch model. For year, 2011 is the baseline in the models, with parameter estimate set to zero.

Response Variable	Parameter	Estimate	SE
Pine	Intercept	1.8271	0.2002
	Mineral soil	0.0328	0.0037
	Other cover	−0.0166	0.0056
	Year 2012	−0.5627	0.2133
	Year 2013	−1.0981	0.2227
	Year 2014	−1.2122	0.2730
Birch	Intercept	0.9833	0.6491
	Mineral soil	0.0258	0.0070
	Other cover	0.0217	0.0087

Table 4. Results from model selection on density of Scots pine and birch seedlings, measured as number of seedlings per sampling point. The table shows the five models with lowest AIC from 24 candidate models for pine and 17 candidate models for birch. Model parameters are presented with corresponding degrees of freedom (Df), AIC value, ΔAIC, and AIC weights. Models are ranked from lowest to highest AIC. The models which were considered the most optimal are written in italics. Abbreviated variable names are: mineral = proportion of exposed mineral soil, humus = proportion of exposed humus, year = year of scarification, other = proportion of other cover, prod = forest productivity index.

Pine Seedling Density	Df	AIC	ΔAIC
mineral + other + year + year × mineral	11	3036.59	0.00
mineral + other + year	8	3036.79	0.20
mineral + humus + other + year	9	3038.64	2.05
mineral + humus + other + year + prod	11	3041.50	4.91
mineral + humus + other + year + prod + year × mineral + year × humus + prod × mineral + prod × humus	21	3041.88	5.29
Birch Seedling Density	**Df**	**AIC**	**ΔAIC**
mineral + other	6	4404.72	0.00
mineral + humus + other	7	4405.69	0.96
mineral + other + year	9	4406.03	1.31
mineral + humus + other + year	10	4406.36	1.64
mineral	5	4409.58	4.86

3.2. Current Annual Growth

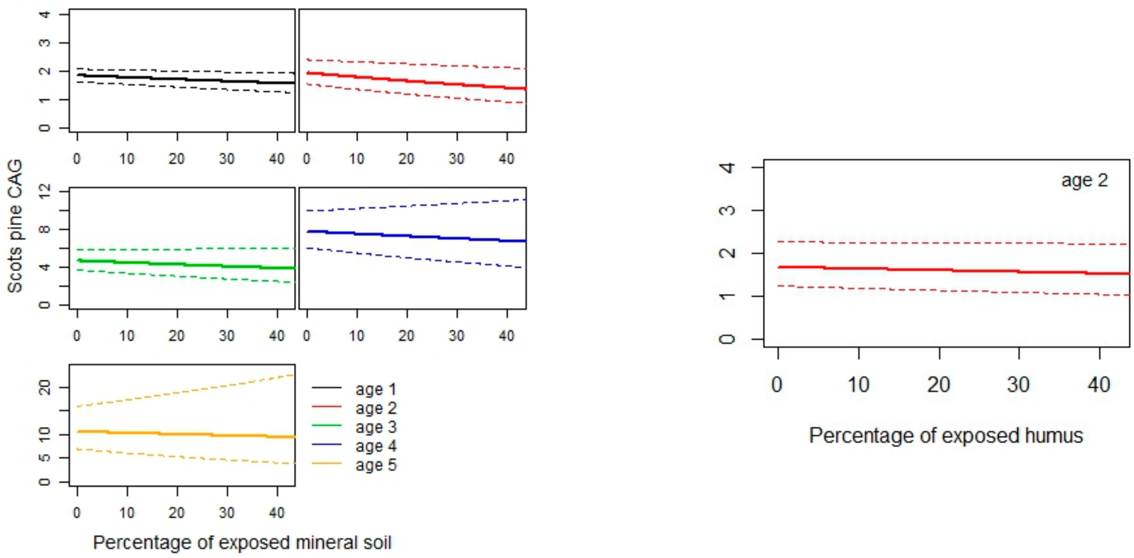
The mean height of trees during the time of the data sampling was 7.4 cm ± SD 7.7 cm for Scots pine, 11.2 cm ± SD 12.3 cm for downy birch > 2 growth season old, and 26.2 cm ± SD 19.1 cm for silver birch > 2 growing seasons old. The small birches which were <2 growth seasons old were excluded from the calculation of the mean because they made up a very large part of the total amount of birches, which made the distribution very right-skewed. Also, the very small birches were not assigned to a specific birch species.

The most optimal model for Scots pine predicted that CAG decreased with increasing proportion of exposed mineral soil (Figure 2a) and proportion of exposed humus (Figure 2b). The decrease in pine CAG with proportion of exposed mineral soil was more apparent for pine seedlings with an age of one to two compared to those with an age of three to five, as can be seen by positive estimates for interaction effects between mineral soil and age (Table 5). The optimal model for downy birch predicted that CAG decreased with increasing proportion of exposed mineral soil (Figure 3a). CAG of downy birch also decreased with increasing proportion of exposed humus for tree seedlings with an age of one to two. For those in the age class 3–4, CAG increased with proportion of exposed humus (Figure 3b). The best model for CAG of silver birch showed, not unexpectedly, that CAG increased with the age of the seedling (Table 5). We did not present the best model for CAG of silver birch as a figure, as scarification intensity was not important in the most optimal model.

The best model for predicting CAG of Scots pine included the explanatory variables: proportion of exposed mineral soil, proportion of exposed humus, age of tree seedling, and an interaction effect between age of tree seedling and proportion of exposed mineral soil (Table 6, pseudo-R-squared adjusted for the effect of the random model structure = 0.56). For CAG of downy birch, the model which included the explanatory variables' proportion of exposed mineral soil, proportion of exposed humus, scarification year, age of tree seedling, an interaction effect between age of tree seedling and proportion of exposed mineral soil, and an interaction effect between age of tree seedling and proportion of exposed humus, was the best model (pseudo-R-squared adjusted for the effect of the random model structure = 0.84, Table 6). The best model predicting CAG of silver birch only included the explanatory variables' age of tree seedling and scarification year (pseudo-R-squared adjusted for the effect of the random model structure = 0.52, Table 6).

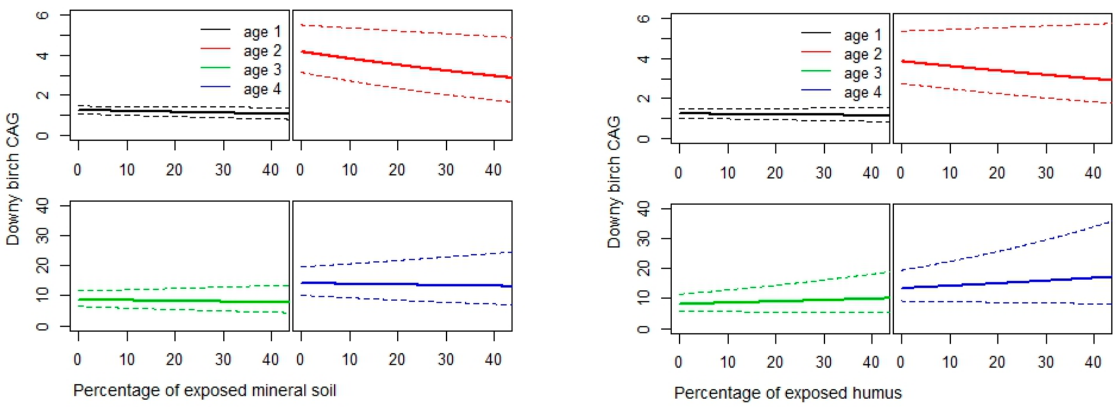
Table 5. Final model parameters with corresponding estimates and standard errors for current annual growth of Scots pine, downy birch, and silver birch, respectively. Models were fitted as LMMs with normal error distribution. The response variable, length of top shoot, was ln-transformed. Plot nested within sampling point nested within stand was included as a random intercept for all models.

Response Variable	Parameter	Estimate	SE
Pine	Intercept	0.6304	0.0506
	Mineral soil	−0.0040	0.0012
	Humus	−0.0023	0.0010
	Age 2	0.0456	0.0517
	Age 3	0.9298	0.0547
	Age 4	1.4411	0.0658
	Age 5	1.7571	0.1505
	Age 2 × mineral soil	−0.0041	0.0014
	Age 3 × mineral soil	−0.0006	0.0015
	Age 4 × mineral soil	0.0006	0.0019
	Age 5 × mineral soil	0.0013	0.0043
Downy birch	Intercept	0.2472	0.0608
	Mineral soil	−0.0040	0.0014
	Humus	−0.0018	0.0016
	Age 2	1.2288	0.0463
	Age 3	1.8562	0.0482
	Age 4	2.3371	0.0578
	Mineral soil × age 2	−0.0046	0.0016
	Mineral soil × age 3	0.0013	0.0018
	Mineral soil × age 4	0.0023	0.0021
	Humus × age 2	−0.0025	0.0016
	Humus × age 3	0.0067	0.0020
	Humus × age 4	0.0075	0.0028
Silver birch	Intercept	0.7419	0.1963
	Age 2	1.1246	0.1884
	Age 3	1.9009	0.1870
	Age 4	2.1541	0.1945



(**a**) (**b**)

Figure 2. Predicted models for current annual growth of Scots pine at different age classes with (**a**) increasing proportion of exposed mineral soil, and (**b**) increasing proportion of exposed humus, here presented for age = 2. The dotted lines indicate the 95% confidence interval. The prediction line for (**a**) is based on an average contribution of the effect of proportion of exposed humus at the mean level of 11% exposed humus. The prediction line for (**b**) is based on an average contribution of the effect of proportion of exposed mineral soil at the mean level of 20% exposed mineral soil. Note the different scale on the Y-axis between age classes 1–2, 3–4, and 5.



(**a**) (**b**)

Figure 3. Predicted model for current annual growth of downy birch top shoots at different age classes with (**a**) increasing proportion of exposed mineral soil, and (**b**) increasing proportion of exposed humus. The dotted lines indicate the 95% confidence interval. The prediction line for (**a**) is based on an average contribution of the effect of proportion of exposed humus at the mean level of 11% exposed humus. The prediction line for (**b**) is based on an average contribution of the effect of proportion of exposed mineral soil at the mean level of 20% exposed mineral soil. Note the different scale on the *Y*-axis between age classes 1–2 and 3–4.

Table 6. Results from model selection on current annual growth of Scots pine, downy birch, and silver birch seedlings, measured as a log (ln) transformed length of top shoot. The table shows the five models with lowest AIC from 38 candidate models for pine CAG, 31 candidate models for downy birch CAG, and 15 candidate models for silver birch CAG. Model parameters are presented with corresponding degrees of freedom, AIC value, ΔAIC, and AIC weights. Models are ranked from lowest to highest AIC. The models which were considered the most optimal are written in italics. Abbreviated variable names are: mineral = proportion of exposed mineral soil, humus = proportion of exposed humus, year = year of scarification, other = proportion of other cover, prod = forest productivity index, age = age of tree seedling.

CAG for Scots Pine	Df	AIC	ΔAIC
mineral + humus + age + age × mineral	15	5751.42	0.00
mineral + humus + prod + age + age × mineral	17	5753.77	2.35
mineral + age + age × mineral	14	5755.25	3.83
mineral + humus + prod + age + age × mineral + prod × mineral	19	5757.59	6.17
mineral + humus + age	11	5757.88	6.46
CAG for Downy Birch	**Df**	**AIC**	**ΔAIC**
mineral + humus + age + age × mineral + age × humus	16	11,193.54	0.00
mineral + humus + prod + age + age × mineral + age × humus + prod × mineral	20	11,198.26	4.72
mineral + humus + other + prod + age + age × mineral + age × humus + prod × mineral + prod × humus	23	11,203.75	10.21
mineral + humus + age + age × humus	13	11,215.04	21.5
mineral + humus + prod + age + age × humus + prod × mineral	17	11,220.62	27.08
CAG for Silver Birch	**Df**	**AIC**	**ΔAIC**
age	8	1242.48	0.00
humus + age	9	1243.25	0.77
mineral + age	9	1243.73	1.25
humus + age + age × humus	12	1244.89	2.41
mineral + humus + age + age × humus	13	1245.94	3.46

4. Discussion

In this study, we have evaluated the effects of soil scarification intensity on both seedling density and current annual growth (CAG) of Scots pine and two species of birch. We found evidence for a positive exponential correlation between the proportion of exposed mineral soil in the sampling point and density of young pine seedlings, which was consistent with our initial prediction. However, we did not find clear evidence for a positive correlation between birch seedling density and soil scarification intensity. Furthermore, our study showed that increased soil scarification intensity had a negative effect on the CAG of both pine and downy birch. The exception was for the oldest downy birch seedlings, those with an age of three to four growing seasons, where proportion of exposed humus in the sampling plot had a positive correlation with CAG. For CAG, the results differed from our initial predictions, as we had expected that CAG would increase with soil scarification intensity regardless of the age of the seedlings.

4.1. Seedling Density

The positive correlation between soil scarification intensity and Scots pine seedling density found in this study was consistent with a study from Poland using other methods of soil scarification intensity [28]. The positive effect we found was strongest for the highest intensities, which we did not achieve on the stand scale, only on the point scale (8 m^2). Pine density increased with increasing proportion of exposed mineral soil, but not with proportion of exposed humus. This suggests that exposed mineral soil is a more optimal substrate for pine germination compared to humus, which is also supported by other studies [32,33,56].

We found that pine density increased with time since soil scarification treatment, as can be expected as more seeds have had time to establish naturally from seed trees and nearby forest. We did not find evidence for an interaction effect between soil scarification intensity and year of scarification, which suggests that overgrowing with other vegetation in the scarified patches was not a limiting factor for pine seedling density in our study. However, the oldest treated stands in our study were merely five growing seasons old, so the scarified patches were not covered with other vegetation yet. The covariate proportion of "other cover" had, as expected, a negative effect on pine seedling density. "Other cover" mostly consisted of water bodies, rocks, and logging residues, and was included in the analysis to correct for habitat considered not suited for germination.

There was some unexplained variation on both the point and stand level in the final pine density model. The unexplained variation on a smaller scale was likely due to local variation in moisture conditions such as soil retention and evaporation, as several studies point to moisture condition as an essential factor explaining pine seedling germination [32,33,35]. Other factors causing variation on a larger scale could be occurrences of good seed years [27], timing of scarification treatment [57], yearly variation in climatic factors [58], spatial variation in climatic factors [59], or density of seed trees or distance to forest edge. However the distance to seed trees has been found to be negligible for the establishment of pine seedlings [27,60], and studies show that pine seeds from nearby stands also contribute to the natural regeneration in clear-felled stands [61,62].

Concerning birch seedling density, which was treated as both downy birch and silver birch seedling density combined, the relationship with soil scarification intensity was less clear. The most optimal model predicted a positive correlation with proportion of exposed mineral soil, but with much variation between stands and study area sites, implying that other factors could be more important than soil scarification intensity. Compared to the model for Scots pine seedling density, little of the residual deviance was explained, which indicates a poor fit of the model to the data. Birch seedling density increased with both variables' proportion of exposed mineral soil and proportion of other cover, and these estimates were fairly similar to each other. As "other cover" often referred to water bodies, the positive correlation was likely due to a positive response to the soil moisture in areas related to bogs and water. Downy birch accounted for the majority of the birch counts, and is known to frequently establish in moist soil [63,64]. Variation in moisture conditions is the most likely explanation for the variation in birch seedling density in our study.

We did not find correlations between the density of birch seedlings and proportion of exposed humus, scarification year, or forest productivity. While humus is important for birch seedling growth, exposed mineral soil is probably more important for birch seedling establishment [30]. Scarification year was probably not as important for birch seedling density as for pine seedling density because the relationship between birch seedling density and the soil scarification treatment was less clear. Birch is known to be a pioneer species which may quickly establish a high number of seedlings with low contribution the following years. Also, some seedlings may have established before scarification.

Forest productivity index was not important for neither Scots pine nor birch seedling density, but this does not necessarily mean that nutrient availability is not important for the density of pine and birch. The forest productivity index used in our analysis might have been too crude for our data as it was retrieved from forestry plans in the area. There was also a low variation in forest productivity. The forest productivity index was not important for birch seedling density as this index was based on pine in the area.

4.2. Current Annual Growth

CAG of Scots pine seedlings decreased with increasing proportion of mineral soil; however, the effect was fairly weak. The negative effect was weakest for the oldest seedlings in the study. Pine CAG also decreased with proportion of exposed humus, but this effect was not age dependent. Results from other studies imply that intraspecific competition may have an effect on higher intensities of soil scarification where the density of seedlings is higher. In the study by

Aleksandrowicz-Trzcińska et al. [28], the best quality of Scots pine seedling was found when using the least intensive mechanical site preparation method, which also produced the smallest density of seedlings. Here, quality was not defined as CAG but as an overall evaluation of length, colour, and vigour of the seedlings. Hence, one could suspect there to be a link between higher seedling densities and reduced quality or growth as a result of competition. However, the seedlings in this study were quite small and with seemingly sufficient spacing in between to avoid considerable intraspecific competition, so we do not deem it likely that intraspecific competition limited growth.

CAG of downy birch seedlings ≤ 2 growing seasons was slightly negatively correlated with soil scarification intensity. However, seedlings with an age of 3–4 growing seasons had a positive correlation with proportion of humus. This might imply that humus is a more important substrate for the CAG of downy birch than bare mineral soil. Karlsson [30] addressed the fact that the growth of birch is better in soils where organic matter is accessible to the roots. In the study by Karlsson, soil tillage had a modest effect on the one-year-old birch seedlings, and a stronger positive effect on the older seedlings, those with an age of two to three years. These results resemble ours. Supposedly, the two to three year-old birch seedlings had longer roots that could reach more nutrient rich soil layers. Another study states that while mineral soil is the best seedbed for birch germination, organic soils are more important for the growth of birch [65]. This could explain why the CAG of birches with an age of two to four increases with proportion of exposed humus in our study. Possibly these seedlings have developed roots that connect with both the mineral soil and the organic humus where the two substrate types have been mixed during the scarification process.

The negative correlation between the CAG of pine and downy birch and soil scarification intensity found in our study may be caused by stress. Young seedlings may experience stress and limited growth of roots due to poor root connection with water [66]. This is similar to stress reported for newly planted seedlings [67], which is shown to limit early growth [68]. Downy birch is a faster-growing species than pine, and may develop roots that are long enough to access more nutrient rich soil layers earlier than pine. This might explain why downy birch seedlings more than two growing seasons old have a positive response to increased soil scarification measured as proportion of humus, while pine seedlings do not. The effect of soil scarification intensity on the growth of both Scots pine and downy birch in our study seems to show an increasingly less negative effect with older seedling age. It is important to further monitor the development of this trend to establish whether the negative effect on early growth is a result of initial plan stress, or whether the effect stays negative over time.

For downy birch, there was a larger variation in CAG compared to Scots pine, which may be linked to a more variable growth in birch than pine. However, measurement errors may be present, as determining age based on counting growth nodes proved to be more challenging for birch than for pine. This is related to the different growth forms of pine and birch [69]. While pine has a predetermined growth with an apical leader [70] and distinguishable shoot-whorls, individual birches may display more variation in growth form. Annual growth nodes in deciduous trees may be hard to distinguish from other shifts in growth or colour that do not represent annual growth.

For silver birch, factors other than soil scarification intensity seemed to play a bigger role, as neither proportion of exposed mineral soil or proportion of exposed humus were important for CAG. Nutrient availability is possibly a more important factor, as silver birch is known to establish in soils rich in lime [71]. Also, silver birch prefers higher temperatures than downy birch. Local climate conditions, such as direction of the terrain in relation to the sun, were also possibly more important for the growth of silver birch.

Several studies point out that mechanical site preparation has a positive effect on the early growth of Scots pine (pine stands one to seven years old) [27,72,73], and a positive long term effect on the growth of Scots pine (pine stands 20–70 years old) [29,74]. Soil scarification is also shown to have a positive effect on the growth of other coniferous trees in other boreal areas of the world (6–25 years old) [31,75,76]. However, a sufficiently high intensity of soil scarification may have undesired effects on growth, as implied by our results. High intensity soil scarification may lead to a higher rate of nutrient leaching and decreased growth due to reduced nutrient availability (32, 67). Still, we did not find support for nutrient availability being a limiting factor for either growth of Scots pine nor birch. Although, nitrogen availability may be a limiting factor for other boreal tree species [71,77]. Downy birch typically grow on nutrient rich soils, while pine tolerate rather nutrient poor conditions [64]. Nevertheless, if the nutrient availability in an area is already low, as in our study where only low and medium-low forest productivity indexes were represented, increased soil scarification intensity might reduce productivity to a point where nutrient availability becomes a limiting factor.

4.3. Management Implications

Increased intensity of soil scarification has been suggested as a mitigation method to increase the density of undamaged pine stems in areas with high moose browsing pressure [78]. In this study, we have shown that increased scarification intensity had a positive effect on densities of pine seedlings at an early stage of stand development, which might lead to higher densities when the stand reaches browsing height. However, it is also important to monitor growth and survival in the coming years, especially because of the negative effects observed on tree growth in this study.

Negative aspects of soil scarification are important to keep in mind when considering using a higher scarification intensity as a means to achieve a more successful regeneration of trees as negative effects might be amplified by the increased intensity. Such negative effects might be increased nutrient leaching due to chemical processes and soil erosion [29,34,79]. Furthermore, the aesthetics of the landscape near populated areas or popular hiking routes need to be considered, as the high intensity of scarification might be perceived as a larger intervention in the landscape compared to the low intensity of soil scarification. The effect on other flora and fauna also needs to be taken into consideration. Knudsen [80] found that the high intensity of soil scarification negatively affected bilberry abundance. Bilberry is an important food source for many animals, including moose, and is therefore important for wildlife diversity [81,82]. Another aspect worth mentioning is the environmental impact. Disturbance of the soil from mechanical site preparation releases CO_2 that has accumulated in the soil into the atmosphere [83], and can in that way contribute to increased emissions of greenhouse gasses.

Based on this research, we would be careful to recommend using high scarification intensity as a means of increasing tree density, as our results show a possible negative effect on growth. Extra caution should probably be taken in sites with low productivity. However, a recently published study from Canada on both planted and naturally regenerated black spruce (*Picea mariana*) showed that positive effects from soil scarification on growth in naturally regenerated stands may take as long as 10–20 years to appear [76]. This implies that it is important to keep monitoring the development of the seedlings over time in order to fully understand the effects of increased intensity of soil scarification. Furthermore, the positive effect we found on seedling density was not very strong. The ratio between density of Scots pine seedlings and soil scarification intensity was less than 1:1 if we only look at densities up to 25% exposed mineral soil, which were the highest achieved densities on the stand level. This means that doubling the scarification intensity will not necessarily double the density of established seedlings. Increasing soil scarification intensity should therefore be carefully weighed against the extra investment. As soil scarification is a widespread method for reforestation [44], our findings may have relevance for other boreal areas of the world under similar preconditions.

5. Conclusions

This study showed that high densities of Scots pine seedlings in naturally regenerated pine stands can be achieved by intensifying soil scarification by exposing a larger proportion of the mineral soil per clear cut area. However, the effect was quite modest when focusing on the highest intensities achieved on the stand scale, compared with smaller scales. Results from this study also indicate a negative effect from soil scarification intensity on growth during the youngest ages for both Scots pine and downy birch seedlings. An evaluation of long term effects on seedling growth is needed in order to understand whether this trend changes with increasing age.

Future research should focus on the long-term effects of a high soil scarification intensity on seedling density, growth, and survival of pine and birch seedlings, and how this in turn will affect cervid browsing in the future. Particularly, this study addresses the need for further knowledge on the effect of a high intensity of soil scarification on long term growth, as well as on higher site productivities than were used in this study.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/5/262/s1, Dataset: Data 2015 Forest and moose.

Author Contributions: M.S. completed the data collection and analyses, and prepared the manuscript. K.M.M. and C.S. designed the study, commented on the results, and edited the manuscript.

Acknowledgments: This study was funded by the Norwegian Research Council's Regional Funds for Inland Norway (Hedmark and Oppland), project number 212525, Forest and moose—can increased forage production reduce browsing damage? In addition, thanks go to the many students from Inland Norway University of Applied Sciences that assisted in the fieldwork: Cloé Montcher, Falk-Rudhard Schreiner, Gaetan Leroux, Jan Kiehne, Peter Holmeier, Petrus Martiskin, Pierre LeQuay, Rohan Richard, and Vincent Baudon.

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

References

1. Bergström, R.; Hjeljord, O. Moose and vegetation interactions in northwestern Europe and Poland. *Swed. Wildl. Res. Suppl.* **1987**, *1*, 213–228.
2. Månsson, J.; Bergström, R.; Pehrson, Å.; Skoglund, M.; Skarpe, C. Felled Scots pine (*Pinus sylvestris*) as supplemental forage for moose (*Alces alces*): Browse availability and utilization. *Scand. J. For. Res.* **2010**, *25*, 21–31. [CrossRef]
3. Lavsund, S.; Nygrén, T.; Solberg, E.J. Status of moose populations and challenges to moose management in Fennoscandia. *Alces* **2003**, *39*, 109–130.
4. Heikkilä, R.; Härkönen, S. Moose browsing in young Scots pine stands in relation to forest management. *For. Ecol. Manag.* **1996**, *88*, 179–186. [CrossRef]
5. Bergqvist, G.; Bergström, R.; Edenius, L. Effects of moose (*Alces alces*) rebrowsing on damage development in young stands of Scots pine (*Pinus sylvestris*). *For. Ecol. Manag.* **2003**, *176*, 397–403. [CrossRef]
6. Storaas, T.; Gundersen, H.; Henriksen, H.; Andreassen, H.P. The economic value of moose in Norway—A review. *Alces* **2001**, *37*, 97–107.
7. Bærekraftig Hjorteviltforvaltning i Hedmark. Available online: https://www.hamar.kommune.no/getfile.php/13408296/Bilder/Hamar/Artikkelbilder/Organisasjonen/R%C3%A5dmann%20og%20staber/Vedlegg%201%20fra%20ERMG%20-%20B%C3%A6rekraftig%20hjorteviltforvaltning%20i%20Hedmark.pdf (accessed on 11 December 2017). (In Norwegian)
8. Solbraa, K. *Elg i Atndal og Naboområder: Forvaltning av Elg og Skog*; 4; Research Report; Hedmark University College: Terningen, Arena, 2008. (In Norwegian)
9. Gundersen, H.; Andreassen, H.P.; Storaas, T. Supplemental feeding of migratory moose *Alces alces*: Forest damage at two spatial scales. *Wildl. Biol.* **2004**, *10*, 213–223.
10. Heikkila, R.; Harkonen, S. Thinning residues as a source of browse for moose in managed forests in Finland. *Alces* **2000**, *36*, 85–92.
11. Edenius, L.; Roberge, J.-M.; Månsson, J.; Ericsson, G. Ungulate-adapted forest management: Effects of slash treatment at harvest on forage availability and use. *Eur. J. For. Res.* **2014**, *133*, 191–198. [CrossRef]
12. Edenius, L.; Månsson, J.; Hjortstråle, T.; Roberge, J.-M.; Ericsson, G. Browsing and damage inflicted by moose in young Scots pine stands subjected to high-stump precommercial thinning. *Scand. J. For. Res.* **2015**, *30*, 382–387. [CrossRef]
13. Haug, F.; Haget, D.; Hekne, A.M.; Hegg, B.R. *Elgbeite på Gran: Takseringi Stange og Våler kommuner 2013*; Fylkesmannen i Hedmark, landbruksavdelingen: Hamar, Norway, 2014; p. 23. (In Norwegian)
14. Lyly, O.; Saksa, T. The effect of stand density on moose damage in young *Pinus sylvestris* stands. *Scand. J. For. Res.* **1992**, *7*, 393–403. [CrossRef]
15. Andren, H.; Angelstam, P. Moose browsing on Scots pine in relation to stand size and distance to forest edge. *J. Appl. Ecol.* **1993**, *30*, 133–142. [CrossRef]

16. Wallgren, M.; Bergström, R.; Bergqvist, G.; Olsson, M. Spatial distribution of browsing and tree damage by moose in young pine forests, with implications for the forest industry. *For. Ecol. Manag.* **2013**, *305*, 229–238. [CrossRef]
17. Bergström, R. Rebrowsing on birch (*Betula pendula* and *B. pubescens*) stems by moose. *Alces* **1984**, *19*, 3–13.
18. Heikkilä, R. Moose browsing in a Scots pine plantation mixed with deciduous tree species. *Acta For. Fenn.* **1991**, *224*, 1–13. [CrossRef]
19. Mathisen, K.M.; Milner, J.M.; Skarpe, C. Moose–tree interactions: Rebrowsing is common across tree species. *BMC Ecol.* **2017**, *17*, 12. [CrossRef] [PubMed]
20. Edenius, L. Browsing by moose on Scots pine in relation to plant resource availability. *Ecology* **1993**, *74*, 2261–2269. [CrossRef]
21. Löyttyniemi, K. On repeated browsing of Scots pine saplings by moose (*Alces alces*). *Silva Fenn.* **1985**, *19*, 387–391. [CrossRef]
22. Danell, K.; Bergström, R.; Edenius, L.; Ericsson, G. Ungulates as drivers of tree population dynamics at module and genet levels. *For. Ecol. Manag.* **2003**, *181*, 67–76. [CrossRef]
23. Siipilehto, J.; Heikkilä, R. The effect of moose browsing on the height structure of Scots pine saplings in a mixed stand. *For. Ecol. Manag.* **2005**, *205*, 117–126. [CrossRef]
24. Karlsson, A.; Albrektson, A.; Forsgren, A.; Svensson, L. An analysis of successful natural regeneration of downy and silver birch on abandoned farmland in Sweden. *Silva Fenn.* **1998**, *32*, 229–240. [CrossRef]
25. Nygaard, P. Rett tid for markberedning. *Aktuelt fra Skogforskningen* **2001**, *6*, 25.
26. Øyen, B.-H. Litt om markberedning i furuskog. *Aktuelt fra Skogforskningen* **2002**, *3*, 47–49.
27. Karlsson, C.; Örlander, G. Soil scarification shortly before a rich seed fall improves seedling establishment in seed tree stands of *Pinus sylvestris*. *Scand. J. For. Res.* **2000**, *15*, 256–266. [CrossRef]
28. Aleksandrowicz-Trzcinska, M.; Drozdowski, S.; Brzeziecki, B.; Rutkowska, P.; Jablonska, B. Effects of different methods of site preparation on natural regeneration of *Pinus sylvestris* in Eastern Poland. *Dendrobiology* **2014**, *71*, 73–81. [CrossRef]
29. Örlander, G.; Egnell, G.; Albrektson, A. Long-term effects of site preparation on growth in Scots pine. *For. Ecol. Manag.* **1996**, *86*, 27–37. [CrossRef]
30. Karlsson, A. Site preparation of abandoned fields and early establishment of naturally and direct-seeded birch in Sweden. *Stud. For. Suec.* **1996**, *199*, 25.
31. Bedford, L.; Sutton, R. Site preparation for establishing lodgepole pine in the sub-boreal spruce zone of interior British Columbia: The Bednesti trial, 10-year results. *For. Ecol. Manag.* **2000**, *126*, 227–238. [CrossRef]
32. Oleskog, G.; Sahlén, K. Effects of seedbed substrate on moisture conditions and germination of Scots pine (*Pinus sylvestris*) seeds in a mixed conifer stand. *New For.* **2000**, *20*, 119–133. [CrossRef]
33. Oleskog, G.; Sahlén, K. Effects of seedbed substrate on moisture conditions and germination of *Pinus sylvestris* seeds in a clearcut. *Scand. J. For. Res.* **2000**, *15*, 225–236. [CrossRef]
34. Piirainen, S.; Finér, L.; Mannerkoski, H.; Starr, M. Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. *For. Ecol. Manag.* **2007**, *243*, 10–18. [CrossRef]
35. Chantal, M.D.; Leinonen, K.; Ilvesniemi, H.; Westman, C.J. Combined effects of site preparation, soil properties, and sowing date on the establishment of *Pinus sylvestris* and Picea abies from seeds. *Can. J. For. Res.* **2003**, *33*, 931–945. [CrossRef]
36. Gaudio, N.; Balandier, P.; Perret, S.; Ginisty, C. Growth of understorey Scots pine (*Pinus sylvestris* L.) saplings in response to light in mixed temperate forest. *Forestry* **2011**, *84*, 187–195. [CrossRef]
37. Hytönen, J. Allelopathic potential of peatland plant species on germination and early seedling growth of Scots pine, silver birch and downy birch. *Silva Fenn.* **1992**, *26*, 63–73. [CrossRef]
38. Hille, M.; Den Ouden, J. Charcoal and activated carbon as adsorbate of phytotoxic compounds—A comparative study. *Oikos* **2005**, *108*, 202–207. [CrossRef]
39. Bryant, J.P.; Chapin, F.S., III; Klein, D.R. Carbon/nutrient balance of boreal plants in relation to vertebrate herbivory. *Oikos* **1983**, *40*, 357–368. [CrossRef]
40. Price, P.W. The plant vigor hypothesis and herbivore attack. *Oikos* **1991**, *62*, 244–251. [CrossRef]
41. De Dios, V.R.; Yoshida, T.; Iga, Y. Effects of topsoil removal by soil-scarification on regeneration dynamics of mixed forests in Hokkaido, Northern Japan. *For. Ecol. Manag.* **2005**, *215*, 138–148. [CrossRef]
42. MacKenzie, M.; Schmidt, M.; Bedford, L. Soil microclimate and nitrogen availability 10 years after mechanical site preparation in northern British Columbia. *Can. J. For. Res.* **2005**, *35*, 1854–1866. [CrossRef]

43. Zaczek, J.J. Composition, diversity, and height of tree regeneration, 3 years after soil scarification in a mixed-oak shelterwood. *For. Ecol. Manag.* **2002**, *163*, 205–215. [CrossRef]
44. Löf, M.; Dey, D.C.; Navarro, R.M.; Jacobs, D.F. Mechanical site preparation for forest restoration. *New For.* **2012**, *43*, 825–848. [CrossRef]
45. Mäkitalo, K. Effect of site preparation and reforestation method on survival and height growth of Scots pine. *Scand. J. For. Res.* **1999**, *14*, 512–525. [CrossRef]
46. Moen, A. *Vegetasjonsatlas for Norge: Vegetasjon*; Lillethun, A., Ed.; Norwegian Mapping Authority: Hønefoss, Norway, 1998.
47. Climate Data, Norwegian Meteorological Institute. Available online: https://www.met.no/frie-meteorologiske-data (accessed on 2 March 2016).
48. Karlsson, C.; Sikström, U.; Orlander, G.; Hannerz, M.; Hånell, B. *Naturlig föryngring Av Tall Och Gran*; 4; Research Report; Skogsstyrelsen: Jonkoping, Sweden, 2009. (In Swedish)
49. Statistics Norway. Klassifisering av Produktivt Skogareal Etter Bonitet (H40) 1997. Available online: http://www.ssb.no/klass/klassifikasjoner/71 (accessed on 26 April 2016). (In Norwegian)
50. Zuur, A.F.; Ieno, E.N.; Elphick, C.S. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* **2009**, *1*, 3–14. [CrossRef]
51. Zuur, A.F.; Ieno, E.N.; Walker, N.J.; Saveliev, A.A.; Smith, G.M. *Mixed Effects Models and Extensions in Ecology with R*; Springer: New York, NY, USA, 2009.
52. Burnham, K.P.; Anderson, D.R. *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*, 2nd ed.; Springer Science & Business Media: Berlin, Germany, 2002.
53. R: A Language and Environment for Statistical Computing. Available online: http://www.R-project.org/ (accessed on 23 January 2016).
54. Bates, D.; Maechler, M.; Bolker, B.; Walker, S. Fitting Linear Mixed-Effects Models Using lme4. *J. Stat. Softw.* **2015**, *67*, 1–48. [CrossRef]
55. Nlme: Linear and Nonlinear Mixed Effects Models. R Package Version 3.1-121. Available online: http://CRAN.R-project.org/package=nlme (accessed on 23 January 2016).
56. Béland, M.; Agestam, E.; Ekö, P.; Gemmel, P.; Nilsson, U. Scarification and seedfall affects natural regeneration of Scots pine under two shelterwood densities and a clear-cut in southern Sweden. *Scand. J. For. Res.* **2000**, *15*, 247–255. [CrossRef]
57. Hörnfeldt, R.; Hu, B.; Chiriacò, M.V. Optimum timing of soil scarification for the natural regeneration of *Pinus sylvestris* in Central Sweden. *Scand. J. For. Res.* **2012**, *27*, 424–431. [CrossRef]
58. Sarvas, R. Investigations on the flowering and seed crop of Pinus silvestris. *Metsät Tutkimuslait Julk* **1962**, *53*, 198.
59. Tegelmark, D. Site factors as multivariate predictors of the success of natural regeneration in Scots pine forests. *For. Ecol. Manag.* **1998**, *109*, 231–239. [CrossRef]
60. Kuuluvainen, T.; Pukkala, T. Effect of Scots pine seed trees on the density of ground vegetation and tree seedlings. *Silva Fenn.* **1989**, *23*, 159–167. [CrossRef]
61. Yazdani, R.; Lindgren, D. Gene Dispersion after Natural Regeneration under a Widely-Spaced Seed-Tree Stand of *Pinus sylvestris*. *Silvae Genet.* **1992**, *41*, 1–5.
62. Ackzell, L. Natural regeneration on planted clear-cuts in boreal Sweden. *Scand. J. For. Res.* **1994**, *9*, 245–250. [CrossRef]
63. Kinnaird, J. Effect of site conditions on the regeneration of birch (*Betula pendula* Roth and *B. pubescens* Ehrh.). *J. Ecol.* **1974**, *62*, 467–472. [CrossRef]
64. Paavilainen, E.; Päivänen, J. *Peatland Forestry: Ecology and Principles*; Springer Science & Business Media: Berlin, Germany, 1995; pp. 134–165.
65. Marquis, D.A. Silvical requirements for natural birch regeneration. In *Birch Symposium Proceedings*; Northeastern Forest Experiment Station: Pennsylvania, PA, USA, 1969; pp. 36–48.
66. Morris, L.; Ludovici, K.; Torreano, S.; Carter, E.; Lincoln, M.; Will, R. An approach for using general soil physical condition–root growth relationships to predict seedling growth response to site preparation tillage in loblolly pine plantations. *For. Ecol. Manag.* **2006**, *227*, 169–177. [CrossRef]
67. Grossnickle, S.C. Importance of root growth in overcoming planting stress. *New For.* **2005**, *30*, 273–294. [CrossRef]
68. Kozlowski, T.T.; Davies, W. Control of water balance in transplanting trees. *J. Arboric* **1975**, *1*, 1–10.

69. Kozlowski, T.T.; Clausen, J.J. Shoot growth characteristics of heterophyllous woody plants. *Can. J. Bot.* **1966**, *44*, 827–843. [CrossRef]
70. Kozlowski, T.T. Shoot growth in woody plants. *Bot. Rev.* **1964**, *30*, 335–392. [CrossRef]
71. Odland, A. *Bjørkeartenes Spredning, Etablering og Samspill med Naturmiljøet*; Nina Report 292; Norwegian Institute for Nature Research: Trondheim, Norway, 1994; pp. 1–50, (In Norwegian, abstract in English).
72. Johansson, K.; Ring, E.; Hogbom, L. Effects of pre-harvest fertilization and subsequent soil scarification on the growth of planted *Pinus Sylvestris* seedlings and ground vegetation after clear-felling. *Silva Fenn.* **2013**, *47*, 18. [CrossRef]
73. Hille, M.; Den Ouden, J. Improved recruitment and early growth of Scots pine (*Pinus sylvestris* L.) seedlings after fire and soil scarification. *Eur. J. For. Res.* **2004**, *123*, 213–218. [CrossRef]
74. Nilsson, U.; Allen, H.L. Short-and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *For. Ecol. Manag.* **2003**, *175*, 367–377. [CrossRef]
75. Nordborg, F.; Nilsson, U. Growth, damage and net nitrogen uptake in *Picea abies* (L.) Karst. seedlings, effects of site preparation and fertilisation. *Ann. For. Sci* **2003**, *60*, 657–666.
76. Prévost, M.; Dumais, D. Long-term growth response of black spruce advance regeneration (layers), natural seedlings and planted seedlings to scarification: 25th year update. *Scand. J. For. Res.* **2018**. [CrossRef]
77. Bergh, J.; Linder, S.; Lundmark, T.; Elfving, B. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *For. Ecol. Manag.* **1999**, *119*, 51–62. [CrossRef]
78. Fremming, O.R.; Knudsen, M.F.; Storaas, T. *Elgbeiteskader på Ungfuru: Avstem Fôrbehov og Fôrproduksjon*; 3; Hjortevilttoget Report; Oplandske Bokforlag: Vallset, Norway, 2014; pp. 107–128. (In Norwegian)
79. Kubin, E. Leaching of nitrate nitrogen into the groundwater after clear felling and site preparation. *Boreal Environ. Res.* **1998**, *3*, 3–8.
80. Knudsen, M.F. Effects of Different Scarification Intensities on Bilberry Abundance. Master's Thesis, Hedmark University College, Easthern, Norway, 2014.
81. Parlane, S.; Summers, R.; Cowie, N.; Van Gardingen, P. Management proposals for bilberry in Scots pine woodland. *For. Ecol. Manag.* **2006**, *222*, 272–278. [CrossRef]
82. Storch, I. Habitat selection by capercaillie in summer and autumn: Is bilberry important? *Oecologia* **1993**, *95*, 257–265. [CrossRef] [PubMed]
83. Conen, F.; Zerva, A.; Arrouays, D.; Jolivet, C.; Jarvis, P.G.; Grace, J.; Mencuccini, M. *The Carbon Balance of Forest Soils: Detectability of Changes in Soil Carbon Stocks in Temperate and Boreal Forests*; Taylor & Francis e-Library: Oxford, UK, 2005; pp. 59–66.