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Effects of site preparation and reindeer grazing on the early-stage success of Scots pine regeneration from seeds in northern Finland and Sweden

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ABSTRACT

The importance of sufficient soil scarification to ensure the regeneration of Scots pine on sub-dry and more fertile sites has been emphasized in many studies. Here we aimed to study, how site preparation intensity affects the early success of natural regeneration and sowing (bare seeds and seed pellets) of Scots pine with or without the reindeer grazing. The study area was located in northern Finland and Sweden where five site preparation methods were compared: unprepared control, logging machine tracks, Huminmix (mixing the mineral soil and organic layer), disc trenching and intensive disc trenching. In each of these we used direct seeding, seed pellets and natural regeneration. Results revealed that even the lightest site preparation methods can provide sufficient regeneration results while the reindeer grazing limits the optimal regeneration result. Huminmix and even the track of the logging machine could provide satisfactory regeneration results both in direct seeding and natural regeneration. This could facilitate the coexistence of forest management, reindeer herding and other land use forms in the same stands and area. The use of seed pellets needs further research, but it may have potential due to lower consumption of seeds and less need for site preparation.

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KEYWORDS
Huminmix; disc trenching; sowing; natural regeneration; artificial regeneration

Introduction

Many studies emphasize the importance of sufficient soil scarification to ensure the regeneration of Scots pine (*Pinus sylvestris*) on sub-dry and more fertile sites (e.g. Hyppönen 2002; Hyppönen et al. 2005). Natural regeneration and sowing aim to approximately 4000–5000 seedlings per hectare, which has been suggested as a successful regeneration result in northern boreal forests (Äijälä et al. 2019). In natural regeneration of pine, 50–100 seed trees per hectare are normally left uncut to ensure the successful regeneration (Äijälä et al. 2019). About 3000 seedlings per hectare can be kept as a minimum limit for growing high-quality timber in seeded stands (Varmola 1996). The number of seedlings needs to be higher in stands regenerated naturally or by sowing compared to planted ones (about 2000 per hectare) due to the clustered spacing of the seedlings especially in natural regeneration.

In addition to ensuring regeneration, soil scarification is needed to make the regeneration operations easier, promote the survival of seeds and seedlings, and enhance the growth of young seedlings. Scarification reduces the competition from the ground layer vegetation, increases the average soil temperature, increases the availability of nutrients for the seedlings, reduces the soil compaction and damage to seeds and seedlings (Örlander et al. 1996). Most evident is the reduction of damages in the case of pine weevil (*Hylobius abietis*, e.g. Leather et al. 1999; Örlander and Nilsson 1999; Heiskanen and Viiri 2005). However, scarification in general disturbs the soil more than needed to improve survival of the planted seedlings (Hyppönen and Hallikainen 2011; Hallikainen et al. 2019) as the needed amount of exposed soil surface could be as low as below 5% (e.g. 0.25 m^2 patch for 2000 seedlings sums up to 500 m^2) but in practical forestry it is normally at least 20% or 30%. On the whole, the increased intensity within the whole regeneration chain does not provide any significant surplus for the further development of the stand (see e.g. Hallsby et al. 2015). Furthermore, the measures should be done according to forestry goals (Karlsson 2013; Karlsson et al. 2015; Ahnlund Ulvcrona et al. 2017; Nuutinen et al. 2021), so the most suitable management schedules for each stand could be selected. Additionally, the logging type is known to have an effect on the potential seed and seedling damage. These have been found to be more pronounced in shelterwood forests than in clear-cuts (Nystrand and Granström 2000).

In the present and tomorrow's forestry lower costs can be reached by reducing the intensity of regeneration tasks by doing only what is necessary to reach the goals. The needs of other land use forms also need to be taken better into

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consideration. For example reindeer (*Rangifer tarandus tarandus*) husbandry, outdoor recreation and tourism have a tendency to restrict soil scarification (e.g. Hallikainen et al. 2006, 2010). Reindeer husbandry and forestry have several types of interactions. In addition to the effects of forestry on reindeer husbandry, some effects are inverse: reindeer grazing has been found to have a negative influence on the establishment of pine seedlings, as a whole (e.g. Helle and Moilanen 1993). Reindeer obviously affect the regeneration of Scots pine throughout the reindeer herding area. Due to the negative influence of reindeer grazing on the regeneration, to study the plain effects of site preparation on the regeneration success would need the exclusion of grazing in a regeneration area. Comparing the results of regeneration using different site preparation methods in grazed and ungrazed sites would also reveal a possible interaction between site preparation and grazing. This would mean that grazing may not have a similar influence on regeneration for all site preparation methods of different intensity levels.

In contrast, also some negative effects of site preparation on reindeer foraging have been noticed. Intensive scarification may reduce reindeer foraging, and their digging in the snow, with its negative effects on seedling establishment (Roturier and Bergsten 2006). Intensive site preparation may affect reindeer abduction in the vicinity of an intensively scarified patch.

Even when there are no foreseen land use conflicts with other land use forms it is rational to minimize the intensity of scarification whenever it is possible, to minimize the costs of site preparation and to provide proper grounds for the other land use forms. To be able to direct the site preparation efforts to those places where the preparation is needed, we need to know the success of regeneration without preparation, in the case of light preparation and for when using conventional site preparation methods.

The economic costs of site preparation form a remarkable part of forest regeneration. In addition, the costs have increased steadily in Finland. The increase in the costs of disc trenching, mounding, patch scarification and ploughing was over 50% in private, non-industrial forests between 2002 and 2014 (Natural Resources Institute Finland 2022). Due to increasing costs, there is increasing pressure to find suitable solutions which provide sufficient regeneration results in an economically sustainable manner. It is also shown that towards the north and towards less fertile sites the profitability of silvicultural investments reduces (Ahtikoski and Hökkä 2020). All this underlines that there is an emerging and urgent need for cost-effective and environmental-friendly regeneration methods especially in the northern parts of Fennoscandia.

The aim of the study was to find out how site preparation intensity affects the early success of natural regeneration and sowing of Scots pine. The latter was studied by using two seed types, bare seeds and seed pellets (which consist of a 1 cm thick 5 cm radius peat disk with 1 seed in the middle, Wennström 2014). Both natural regeneration and direct seeding were studied on grazed and non-grazed treatment plots in northern Finland and Sweden. Natural regeneration and the growth of naturally regenerated Scots pine seedlings were also monitored to study the effects of various site preparation methods and reindeer grazing on the early success of Scots pine in the natural regeneration. The study questions were: (1) can we improve the regeneration success and growth using light site preparation methods to avoid conflicts with other land use modes, (2) does seed pellet improve regeneration success, (3) is regeneration improved if we exclude reindeer by using exclosures, (4) is natural regeneration using the seed tree method enough for successful regeneration or is direct seeding needed?

Material and methods

The study area is located in northern Finland and Sweden (Figure 1) about 240–300 meters above sea level. The climatic conditions in the area are quite harsh. The monthly average temperatures in the closest available meteorological station (Kittilä) vary from −12.1°C in January to 14.5°C in July and the average temperature sum is about 800–850 dd (Finnish Meteorological Institute 2022).

The study was based on a completely randomized block design. The blocks are represented by randomly selected experimental forest stands. The stands were selected from a set of preselected stands on sub-dry sites that were accepted after visiting the sites to check that they filled the requirements. In total there were six blocks (i.e. experimental stands), three in Finnish Lapland and three in Norrbotten in Sweden close to the border of Finland and Sweden (Figure 1). Finnish Lapland and Swedish Norrbotten are both reindeer grazing areas, where reindeer graze freely throughout the year. Ten rectangular treatment plots 30 m × 15 m in size were randomly positioned inside each block. Half of the plots were fenced to prevent reindeer grazing (Figure 1). In each rectangular treatment plot there were five 10 m^2 circular sample plots to monitor natural regeneration. In addition, 40 seeding points, half of which were sowed using direct seeding (bare seeds, micro-preparation using five seeds in each) and half using seed pellets, were positioned inside each treatment plot (Figure 1). Seed pellets were simply placed on the ground (i.e. they were not submerged as in some earlier studies, e.g. Wennström 2014). For direct seeding the seeds were covered by 0.5–1 cm of mineral soil, which protects the seeds from drying, frost and predation (Kinnunen 1992). When comparing the success of bare seeds and seed pellets, one should keep in mind the different number of seeds in the pellets (1) and direct seeding (5).

On the 10 rectangular treatment plots five site preparation methods were randomly allocated: (1) control (i.e. no site preparation), (2) driving around with a logging machine, (3) Huminmix, (4) disc trenching and (5) double disc trenching. In the logging machine treatment only a small proportion of the mineral soil is exposed. Huminmix is a light method in which the humus and mineral soil are mixed. As a result, it creates a narrow track with a mixture of the humus layer and mineral soil of about 10–20% of the total area (Roturier and Bergsten 2006; Roturier et al. 2011). Disc trenching is a widely used method in Finland and Sweden. It makes 60–80 cm wide tracks, which are about 1.8–2 meters apart

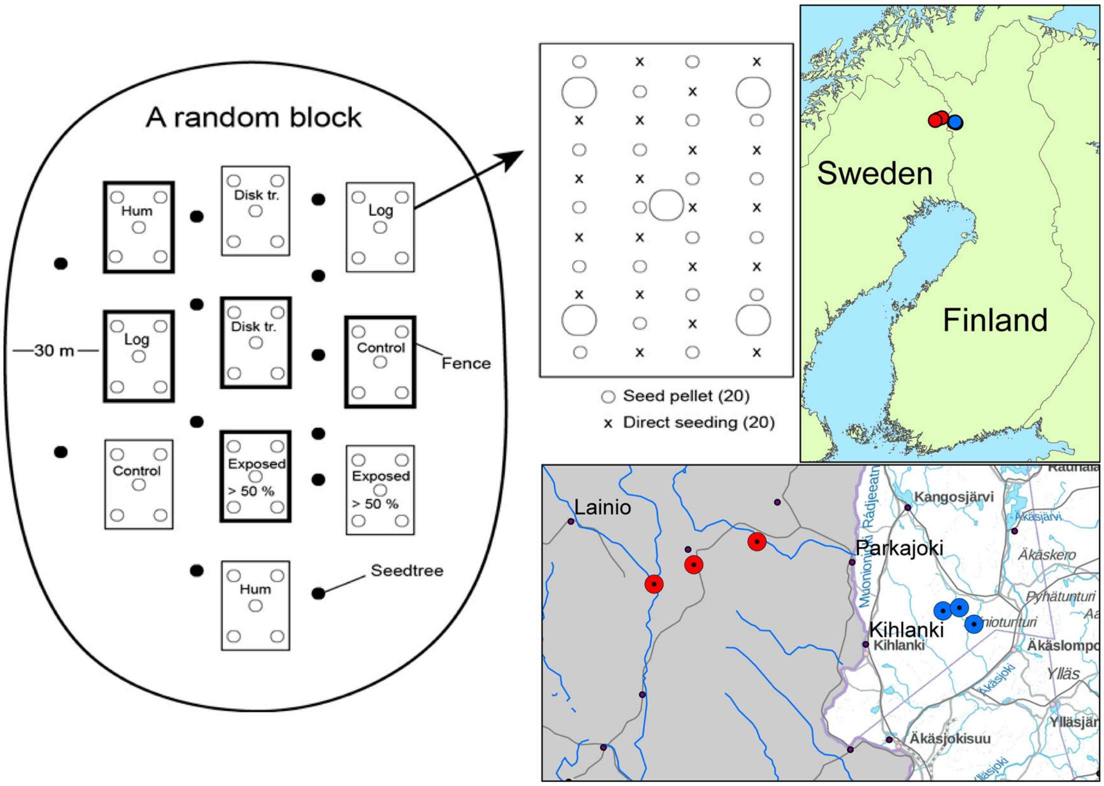

Figure 1. The location of the experimental stands (= blocks) and the study design. Rectangles indicate treatment plots (Control: no site preparation, Hum: huminmix, Log: logging machine, Disc tr.: disc trenching, Exposed >50%: double disc trenching). Small circular symbols within a rectangular treatment plot indicate a spot for seeding, crosses indicate seed pellets and large circular symbols indicate sample plots to monitor natural regeneration. Bolded rectangles indicate the fenced treatment plots. The size of each treatment plot is 30 m × 15 m and the size of each circular sample plot for natural regeneration is 10 m^2.

from each other. As a result, 30–50% of mineral soil is exposed (Karlsson and Örlander 2000). Double disc trenching is an intensive treatment with ≥ 50% of mineral soil exposed (more detailed characteristics of scarification methods are presented in Appendix 1 in Figure A1.1).

Half of the 30 m × 15 m treatment plots (five in every block = experimental stand) were fenced to study the effects of reindeer grazing. The undisturbed vegetation cover and the cover of exposed mineral soil or humus and disturbed vegetation cover were inventoried for the seeding points (with a radius of 3 cm around the seeding point) and in the 10 m^2 circular sample plots in 2013. The number and the height of the seedlings at the seeding points and on the 10 m^2 sample plots were inventoried in 2015, 2016 and 2019. The first and the last inventory year (2015 and 2019) were used in the statistical modeling of the results.

When modeling the natural regeneration, a generalized linear mixed model with negative binomial distribution assumption and log-link function was constructed to model the number of seedlings on the 10 m^2 sample plots (seedling density model). The model consists of three hierarchical levels: block, rectangular treatment plot nested within block and circular sample plot nested within the treatment plot. The model was computed using R-package glmmTMB.

In the R function glmmTMB the variance was defined in two ways: the NB1 variance $= \mu(1+\alpha)$ and NB2 variance $= \mu\left(1+\frac{\mu}{\theta}\right)$ (Brooks et al. 2017). The NB1-parametrization suggested a linear mean-variance relationship, while NB2-parametrization suggested a quadratic relationship. The different parametrizations led to slightly different model fit, parameter estimates and tests. The NB1 model produced a slightly better model fit based on the residuals, but the best fit based on the AIC-values was obtained using NB2-parametrization. However, the parametrization did not considerably affect the interpretation of the results and, hence, NB2-parametrization was used in the final presented model.

R-package glmmTMB allowed also the zero-inflation modeling, but the zero-inflation was not an obvious problem in the data tested by R-package DHRMa (Hartig 2021). The null hypothesis of the suitable number of observed zeroes compared to the simulated ones tested using function testZeroInflation remained ($p = 0.584$). The simulated distribution using the model parameters size and mu were plotted against the observed count distribution to determine the overall model fit. The parameter size was computed using the predictions of the marginal model using the formula $size = \frac{mu^2}{var - mu}$, where *mu* denotes expected mean and *var* the variance of the predicted distribution. The (pseudo) R2-values for the model was computed in two ways: (1) based on the likelihood ratio (Bartoń 2020) and (2) using wide-functioning new R-package performance (Lüdecke et al. 2021).

When modeling the direct seeding (5 seeds) and seed pellets/pellets (1 seed), a generalized linear mixed model with a binomial distribution assumption and logit-link function was constructed to model the dichotomous response for the seeding-point level in 2015 and 2019: 1 = germinated seed and survived seedling, 0 = non-germinated seed or dead seedling. For direct seeding the term "established" denoted that at least one of the five seeds had established and survived. The model consisted of three hierarchical levels: block, rectangular treatment plot nested within the block (level 2) and seeding point nested within rectangular treatment plot. The dispersion parameter of binomial distribution was estimated (not fixed as 1). The model was computed using R-package MASS (Venables and Ripley 2002).

The height of the seedlings established naturally in the 10 m^2 circular sample plots was modeled by using the log-transformed height of the seedlings (measured in 2019) as the response variable in the model. The age of the seedlings and its possible exponents giving the best fit of the model were used as the covariate in the model. The model was computed using R-package nlme (Pinheiro et al. 2020).

There were several fixed explanatory variables and their interactions that were tested in the direct seeding model: (1) fencing (fenced, non-fenced); (2) site preparation (control, logging machine, Huminmix, disc trenching, double disc trenching, i.e. intensive treatment with ≥ 50% of mineral soil exposed); (3) seed type (bare seed. seed pellet); (4) seed bed (mineral soil, mix of humus and mineral soil, humus, disturbed vegetation, undisturbed vegetation); (5) field layer vegetation (*Calluna vulgaris, Vaccinium vitis-idaea, Vaccinium uliginosum, Vaccinium myrtillus, Empetrum nigrum,* grasses spp., no vegetation); (6) ground layer vegetation (in the case of direct seeding: *lichens* spp., *Hylocomium splendens/Plurozium schreberi, Dicranum* sp./ *Polytrichum* sp., no vegetation). In the models for seedling density and height (models for 10 m^2 circular sample plots) seed type and seed bed were not included but fencing and soil treatment were tested similarly to the sowing model and in addition the field layer vegetation (similarly to the sowing models) and the covers of *lichens* spp., *mosses* spp., cover of mineral soil, disturbed and undisturbed vegetation.

The grazing effect (fenced or non-fenced) and site preparation method as well as their interaction were the most important variables in the models because of the study design. The variables, such as cover of mineral soil, disturbed or undisturbed vegetation could not be included in the same model with the site preparation method, because these covariates were highly influenced by the soil treatment. However, the cover of the ground- and field layer species (or species groups) could be tested as the covariates in the models. The vegetation illustrated the site type, basically not affected by the soil treatment.

In addition, the relationships between the field layer species, bilberries (*Vaccinium myrtillus*), cowberries (*Vaccinium vitis-idaea*), crowberries (*Empetrum nigrum*) and heather (*Calluna vulgaris*) as well as the relationships between the ground layer species and cover of moss and lichen species were studied using generalized linear mixed model with a quasi-Poisson distribution family using the hierarchy that have been described above in the random part of the seedling density models. The so-called "quasi-Poisson" (over-distributed Poisson distribution) could fit better than a normal distribution to the models for the vegetation cover data. The relationships were tested using the covers measured at the beginning of the study (year 2013). They might have been slightly changed during the six years period, but the change would have been small at these northern sub-dry sites.

The fixed variables of the factorial random block design were fencing (i.e. grazed or non-grazed), site preparation and their interaction. In addition, the site types were considered using the covariates of the vegetation cover describing the moist-xeric dimension. Several combinations of the species covers were tested as the covariates in the seedling density model, and the most effective variables and their interactions were selected based on the AIC-values (minimize) and pseudo-R^2 values (maximize). The ground-layer vegetation could be described by using the moss or lichen cover as covariates in the model. The time (year 2015 and 2019) was taken in the model to see the development in the seedling density. The interaction effect of the year (categorical, 2015, 2019) was tested with the factors of fencing and soil treatment, but the interactions were not statistically significant at a 5% risk level and, thus, they were left out of the model. The time effect (years 2015 and 2019) was also tested in the random part of the model version in addition to the fixed effect. However, its variance was small, and the random year effect had no effect on the parameter estimates or tests. Thus, in the final version it was left out of the random part of the model and treated only as a fixed variable in the model. The variables in the final model version were the year, fencing, soil treatment, lichen and moss cover, heather cover, and the interaction of fencing and soil treatment. The (pseudo) coefficients of determination (R^2) of the marginal model (fixed predictors only) were about 32.8% (based on the LR-change between the null model and the presented model) or 57.5% (based on R-package performance).

A ratio correction (observed/predicted mean) for the predictions of the log-transformed response linear model (seedling height model) and log-link negative binomial model (seedlings density model) was done (Snowdon 2011). All the analyses and statistical graphs were done using R statistical environment (R Core Team 2019).

Results

Seedling densities in natural regeneration

The "heaviest" soil treatment resulted in less naturally regenerated seedlings than the other treatments (Figure 2(a)). In general, the point estimates suggest that the number of seedlings decreased with the intensity of the soil treatment, but, on the other hand, the confidence intervals show a large variation within the other soil treatment methods except for the most intensive (Figure 2(a)).

The reindeer grazing (fenced vs. non-fenced treatment plots) had a minor effect on the seedling establishment (see also Figure A1.5 in Appendix 1 for more detailed results). The interaction effect of fencing and soil treatment was statistically significant at a 5% risk level (Table 1). The

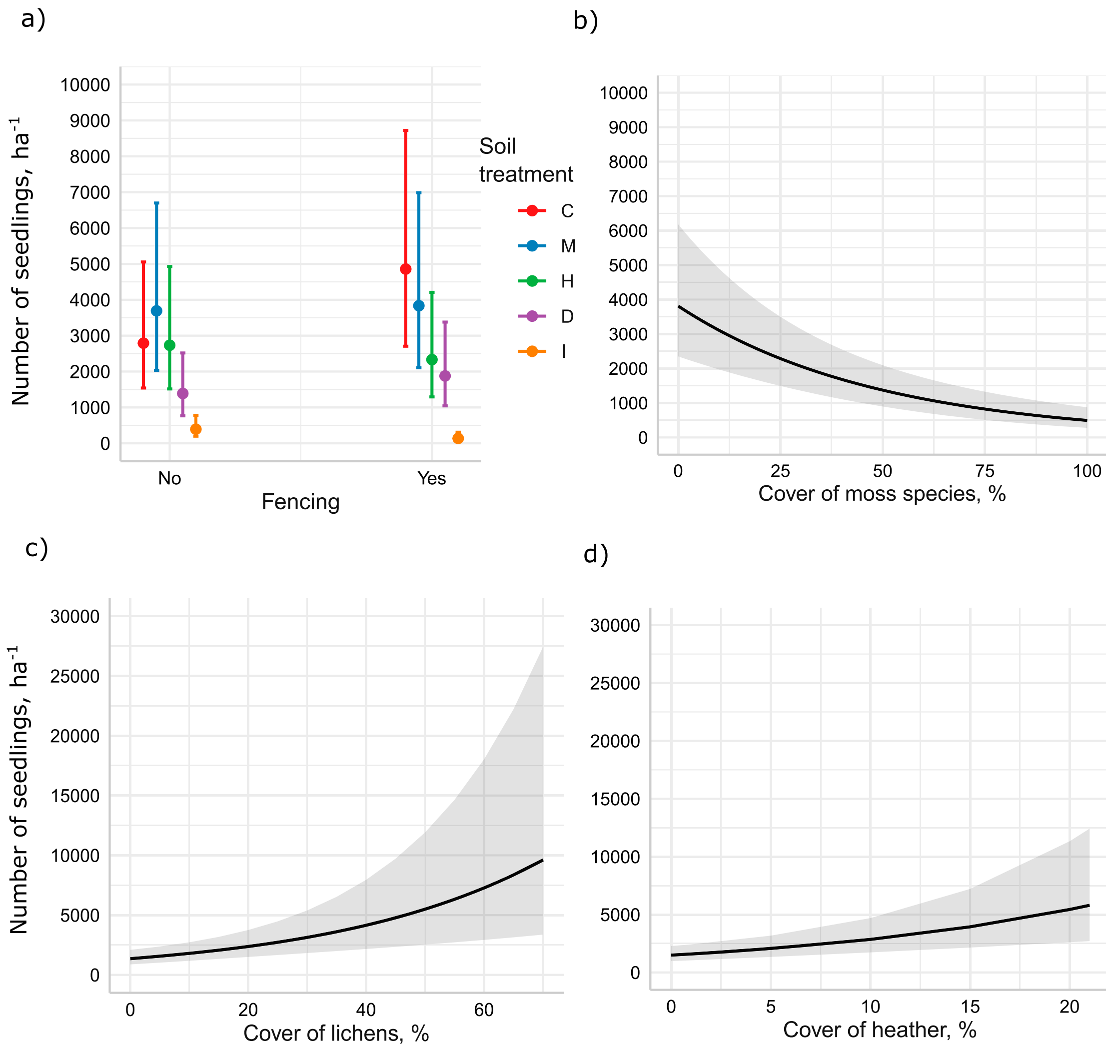

Figure 2. (a–d) The predictions and 95% confidence intervals of the seedling density model for naturally regenerated seedlings: the interaction of fencing and soil treatment (a), moss species cover (b), lichen cover (c) and heather cover (d). In the predictions, the other predictors in the model were set into their mean values or levels. The abbreviations: C = control (approximately 0—1% of mineral soil exposed), M = logging machine (appr. 1—5% of soil exposed), H = Huminmix (10—20% of soil exposed), D = disk trenching (30—50% of mineral soil exposed) and I = intensive (> 50% of mineral soil exposed). See Figure A1.1c in Appendix 1 for the proportions of exposed mineral soil.

number of seedlings in the control (C) was slightly higher in the fenced plots, though the 95% confidence intervals in Figure 2(a) suggests that there were no significant differences between the fenced and non-fenced plots. However, in the most intensively treated plots there were slightly more seedlings in the non-fenced plots compared to the fenced ones (Figure 2(a)).

The predicted number of seedlings increased during the four years (2015–2019) from 1115 to 2731. The increase was quite similar for the different soil treatments and in the fenced and non-fenced plots (no significant interaction). Furthermore, increasing moss cover was connected to a decreasing number of seedlings, whereas increasing lichen and heather cover were connected to higher seedling densities (Table 1, Figure 2(b–d)). It should be emphasized that although the lichen and moss cover correlated to a certain degree, both had a highly significant contribution in the model (Table 1). Furthermore, the VIF-values of these variables were low suggesting a low multicollinearity (cover of moss species 1.66, lichen cover 1.37).

Establishment in direct seeding

The establishment probabilities of the seed pellets (containing one seed) were lower, 0.43, compared to the direct seeding (with five bare seeds), which achieved establishment probability 0.71. Even though the performance of the seed pellets was slightly better compared to the direct seeding in non-treated soils (control) two years after seeding, six years after seeding (2019) the performance of seed pellets was poorer compared to bare seeds (Figure 3(a)). After six years and pellets used, the Huminmix treatment showed the lowest survival rates. On average the establishment probability was about 30% lower in 2019 compared to the situation in 2015 (0.72 vs. 0.41). When using bare seeds the establishment probability was good for all site preparation methods exposing mineral soil (Huminmix, disc trenching and intensive treatment). However, the probability of establishment decreased in four years (from 2015 to 2019) also for these treatments (Figure 3(a), Table 2).

Table 1. Parameter estimates and tests of the generalized linear mixed effects model for the density of naturally regenerated seedlings using a negative binomial distribution assumption (NB2-parametrization).

Variable/Parameter	Estimate	Std. error	z-value / chi-value	*p*-value
Fixed effects				
(Intercept)	1.129	0.373	3.025	0.002
Fencing (ref. Non-fenced)	-	-	3.372 (1)	0.066
–Fenced	0.554	0.302	1.836	0.066
Soil treatment (ref. Control)	-	-	39.069 (4)	< 0.001
–Logging machine	0.280	0.320	0.874	0.382
–Huminmix	−0.021	0.316	−0.067	0.947
–Disc trenching	−0.698	0.329	−2.122	0.034
–Intensive (exposed mineral soil > 50%)	−1.961	0.384	−5.113	< 0.001
Year (ref. 2015)	-	-	82.528 (1)	< 0.001
–2019	0.895	0.099	9.084	< 0.001
Cover of mosses, %	−0.020	0.003	−6.298	< 0.001
Cover of lichens, %	0.028	0.008	3.557	< 0.001
Cover of heather, %	0.064	0.017	3.813	< 0.001
Fencing * Soil treatment (ref. Non-fenced, Control)	-	-	10.321 (4)	0.035
–Yes * Logging machine	−0.516	0.435	−1.187	0.235
–Yes * Huminmix	−0.712	0.440	−1.619	0.105
–Yes * Disc trenching	−0.252	0.435	−0.580	0.562
–Yes * Intensive	−1.609	0.529	−3.044	0.002
Random effects	Variance	95% confidence intervals		
Block	0.234	0.063–0.869		
Treatment plot nested within block	0.160	0.078–0.353		

Notes: Std. error denotes the standard error of the estimate. $R^2 = 32.8\%$ (marginal model, based on the LR-change between the null model and the presented model) and 57.5% (marginal model based on R package performance). For all fixed effects presenting a categorical variable tests for the other treatment categories vs. a reference category (given in parenthesis) are also presented.

The fenced (non-grazed) sites were slightly better sites for seedling establishment, the point estimate of probability being almost 10% higher at the fenced seeding points compared to the non-fenced ones (Figure 3(b)). Furthermore, the establishment of the sowed seedlings was considerably better at the seeding points dominated by either lichen or bare humus or mineral soil (category None in Figure 3(c)) compared to moss-covered seeding points.

Height development of naturally regenerated seedlings

There were no considerable or statistically significant differences between the soil treatments or fencing in the height development of the seedlings (Table 3). However, the seedlings which underwent the intensive treatment in fenced plots were about 10 cm taller compared to the other soil treatment in fenced or non-fenced plots (Figure 4(a)). The point estimates suggest that seedlings in the disk trenching and intensive treatment in the non-fenced plots were slightly (about 5 cm) taller compared to the other soil treatments in the non-fenced plots. But, then again, the 95% confidence intervals suggest that these differences are only indicative.

The naturally regenerated seedlings grew from 10 to 20 cm between 2015 and 2019 (Figure 4(b)). The increasing cover of moss species (indicating a moister site) from 0 to 100% was reflected in the increased growth of about 5 cm during the seven years of the experiment (from the beginning of the experiment to 2019; Figure 4(c)). Increasing of crowberry and especially heather cover reduced the growth of the seedlings (Figure 4(d,e)).

Discussion

The most striking results that we found were the opposite regeneration results for direct seeding and the results of natural regeneration using the seed tree method in relation to site preparation. In direct seeding the best survival of seedlings was found when site preparation was used, but in natural regeneration the best regeneration success was reached when only the lightest site preparation methods were used or site preparation was not used at all. In direct seeding, the survival of seeds was generally good when using heavier site preparation, most likely because the seeds were covered by 0.5–1 cm of mineral soil, which probably provided a shelter against drought, heavy rainfall, frost and predation (see e.g. Kinnunen 1992). In direct seeding the site preparation was beneficial for the seedling survival, but either there the preparation method did not need to be intensive. In fact, even Huminmix, which is a somewhat lightweight site preparation method and exposes only about 10% of the total area, had higher probability of seedling survival than disc trenching, double disc trenching or logging machine preparation. Huminmix has shown encouraging results also in earlier studies in the light of seedling establishment (Erefur et al. 2008), reindeer lichen recovery (Roturier et al. 2011) or both (Roturier and Bergsten 2006).

The results of direct seeding suggest that all site preparation methods studied here can improve regeneration success, but the lightest site preparation methods (Huminmix and even the track of the logging machine) could provide satisfactory regeneration results. This could facilitate the coexistence of forest management, reindeer herding and other land use forms in the same area. This is supported by the results of Hyppönen and Hallikainen (2011) who found a relatively high number of seedlings when only 1–25% of mineral soil was exposed. In their (Hyppönen and Hallikainen 2011) study exposing more mineral soil (26–50% and 51%) the increase in the number of seedings compared to 1–25% mineral soil exposition was rather small. Seed pellets gave somewhat mixed results. The proportion of surviving seeds from the seed pellets was quite low, especially in 2019, in relation to direct seeding and compared to the results obtained using seed pellets in Sweden (Wennström 2014). Our findings do not directly support the use of seed pellets. It is, however, important to note that the seed pellets contained only one seed, while in direct seeding the number at all seeding points was five. Moreover, the performance was better if the soil was not prepared at all or was prepared only by the logging machine. Additionally, the difference between 2015 and 2019 is noteworthy. The mortality of seeds in seed pellets between 2015 and 2019 in Huminmix and in both disc trenching treatments was drastic and needs further research.

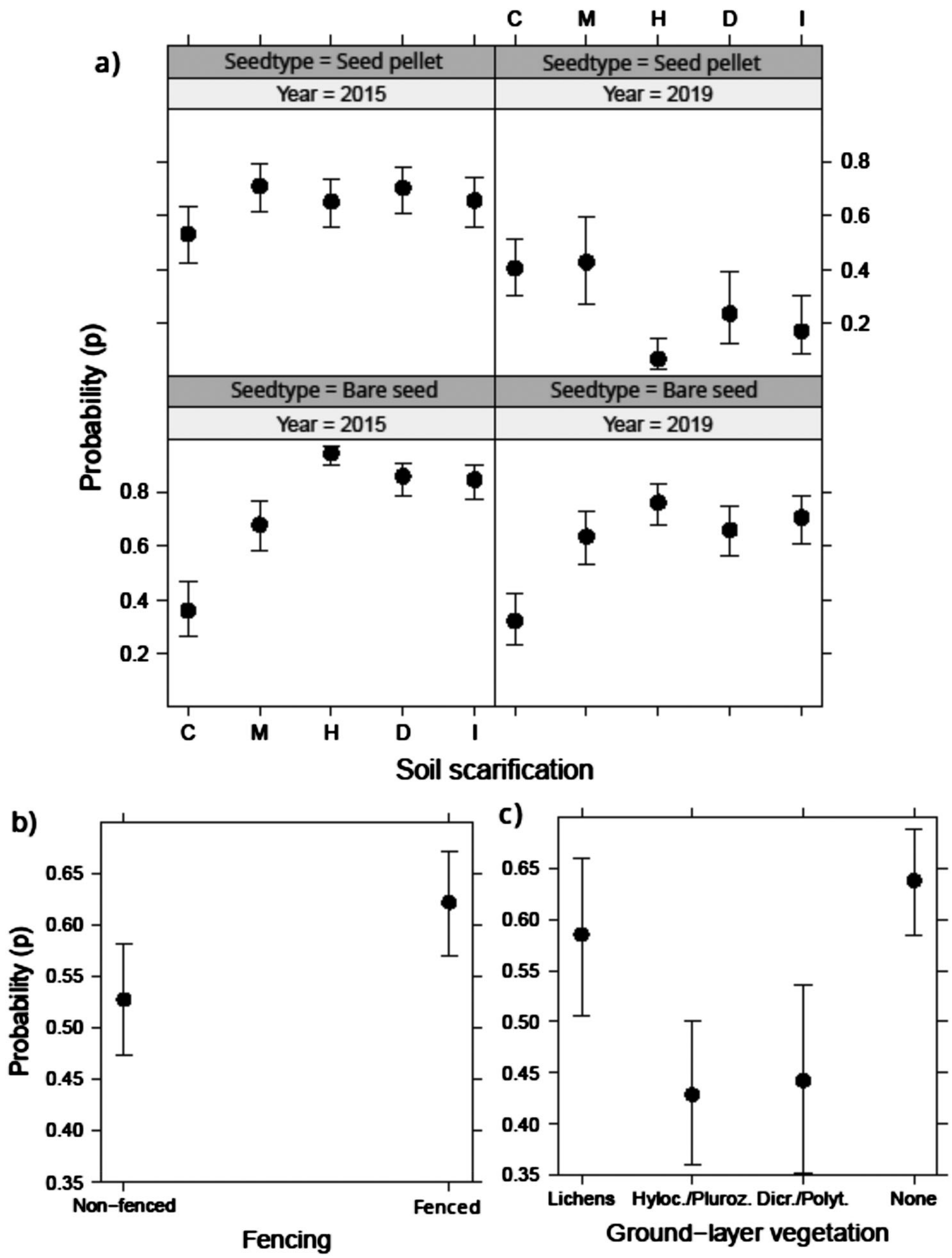

Figure 3. (a–c) The predictions and 95% confidence intervals of the logistic sowing model: the interaction effect of year, seed type and site preparation (a), fencing effect (b) and ground-layer vegetation effect (c). Abbreviations: C = control, M = logging machine, H = Huminmix, D = disc trenching and I = intensive (> 50% of mineral soil exposed), Hyloc. = *Hylocomium splendens*, Pleuroz. = *Pleurozium schreberi*, Dicr. = *Dicranum spp*. and Polyt. = *Polytrichum spp*.

Despite the large mortality with some treatments, the use of seed pellets could be a good option on some occasions. It is known that the required number of seeds depends on the seed quality and site preparation (Wennström et al. 1999, 2002). For example, if the seeds are expensive (high-quality bred seeds) or there is a shortage of seeds, the use of seed pellets may reduce the number of seeds needed noticeably in comparison to automatic sowing. It is also good to note that the use of seed pellets can provide more regular spacing of seedlings, which leads to a lower number of seedlings needed per hectare. Additionally, even if the number of seed pellets would be doubled due to lower survival rates, the needed amount would still only be a fraction of the amount needed during automatic sowing. Furthermore, the increasing price of site preparation (Natural Resources Institute Finland 2022) or seeds may increase the need for methods in which the consumption of seeds is lower to limit the total costs of regeneration. Perhaps the next development step could be towards "lean" thinking, where the scarification intensity would counteract with the secondary supply of seeds or seedlings.

In natural regeneration, the best survival of seedlings was when no site preparation was carried out or the intensity of the site preparation was low. In an earlier study by Hallikainen et al. (2019) successful regeneration was achieved in Finnish Lapland in most cases with site preparation that exposed about 20% of the soil surface. Their estimate for the sufficient amount of exposed mineral soil was 10–20%. Our

Table 2. Parameter estimates and tests of the generalized linear mixed model for the number of the sowed seedlings using binomial distribution assumption.

Variable/Parameter	Estimate	Std. error	df	t- /chi-value	*p*-value
Fixed effects					
(Intercept)	−0.729	0.219	4722	−3.335	0.001
Year (ref. 2015)	-	-	1	0.706	0.401
–2019	−0.171	0.205	4722	−0.837	0.402
Seed type (ref. Bare seed)	-	-	1	13.001	< 0.001
–Seed pellet	0.703	0.195	4722	3.597	0.000
Fencing (ref. Non-fenced)	-	-	1	8.457	0.004
-Fenced	0.388	0.134	49	2.901	0.006
Soil treatment (ref. Control)	-	-	4	83.020	< 0.001
–Logging machine	1.323	0.273	49	4.853	0.000
–Huminmix	3.362	0.407	49	8.266	0.000
–Disc trenching	2.364	0.355	49	6.664	0.000
–Intensive	2.269	0.350	49	6.476	0.000
Ground-layer vegetation (ref. Lichens)	-	-	3	35.706	< 0.001
–*Hylocomium / Pleurozium*	−0.632	0.134	4722	−4.706	0.000
–*Dicranum / Polytrichum spp.*	−0.576	0.185	4722	−3.111	0.002
–No vegetation (None)	0.223	0.201	4722	1.108	0.268
Year * Soil treatment	-	-	4	24.304	< 0.001
–2019 * Logging machine	−0.026	0.277	4722	−0.092	0.927
–2019 * Huminmix	−1.458	0.391	4722	−3.727	0.000
–2019 * Disc trenching	−0.961	0.319	4722	−3.014	0.003
–2019 * Intensive	−0.655	0.317	4722	−2.068	0.039
Year * Seed type	-	-	1	1.445	0.229
–2019 * Pellet	−0.337	0.281	4722	−1.199	0.231
Year * Seed type * Soil treatment	-	-	8	103.661	< 0.001
–2015 * Pellet * Logging machine	−0.560	0.271	4722	−2.063	0.039
–2019 * Pellet * Logging machine	−0.647	0.275	4722	−2.355	0.019
–2015 * Pellet Huminmix	−2.866	0.380	4722	−7.551	0.000
–2019 * Pellet * Huminmix	−1.241	0.290	4722	−4.282	0.000
–2015 * Pellet * Disk trenching	−1.639	0.316	4722	−5.190	0.000
–2019 * Pellet * Disk trenching	−0.548	0.284	4722	−1.933	0.053
–2015 * Pellet * Intensive	−1.752	0.308	4722	−5.683	0.000
–2019 * Pellet * Intensive	−1.046	0.286	4722	−3.651	0.000
Random effects	Variance	95%'s confidence intervals			
Block	$9.964e^{-3}$	$4.458e^{-5}$–2.227			
Treatment plot nested within block	0.201	0.120–0.337			
Dispersion parameter	0.971	0.930–1.013			

Notes: Std. error denotes standard error of estimate and df denotes the degrees of freedom. Classification efficiency (area under ROC-curve) of the model was 73.1%. For all fixed effects presenting a categorical variable also tests for the other treatment categories vs. a reference category (given in parenthesis) are presented.

Table 3. Parameter estimates and tests of the linear mixed effects model for seedling height (log-normal distribution assumption).

	Estimate	std. error	Df	*t*- / chi-value	*p*-value
Fixed effects					
(Intercept)	1.772	0.122	603	14.542	0.000
Fencing (ref. Non-fenced)	-	-	1	1e-4	0.991
–Fenced	−0.001	0.103	43	−0.011	0.991
Soil treatment (ref. Control)	-	-	4	8.467	0.076
–Logging machine	0.092	0.110	43	0.837	0.407
–Huminmix	−0.028	0.111	43	−0.251	0.803
–Disc trenching	0.234	0.110	43	2.127	0.039
–Intensive	0.248	0.133	43	1.871	0.068
Age of seedling (years)	0.161	0.013	603	12.425	0.000
Cover of mosses, %	0.003	0.001	115	2.781	0.006
Cover of heather, %	−0.018	0.006	115	−3.102	0.002
Cover of crowberry, %	−0.009	0.004	115	−2.241	0.027
Fencing * Soil treatment	-	-	4	9.460	0.051
–Fencing * Logging machine	0.027	0.151	43	0.179	0.859
–Fencing * Huminmix	0.141	0.153	43	0.923	0.361
–Fencing * Disk trenching	−0.163	0.152	43	−1.073	0.289
–Fencing * Intensive	0.455	0.210	43	2.164	0.036
Random effects	Variance	95% confidence intervals			
Block	$2.595e^{-3}$	$8.807e^{-5}$–0.076			
Treatment plot nested within block	0.016	0.006–0.044			
Residual	0.073	0.065–0.082			

Notes: Std. error denotes the standard error of estimate and df denotes the degrees of freedom. The R^2 of the model = 24.2% (marginal model). For all fixed effects presenting a categorical variable, tests for the other treatment categories vs. a reference category (given in parenthesis) are also presented.

results showed that an even lower proportion of exposed mineral soil could be sufficient. This suggests even more careful consideration of the intensity and method of the needed site preparation. This finding may help to minimize the management costs, environmental effects and the adverse effects of site preparation on the other land use forms.

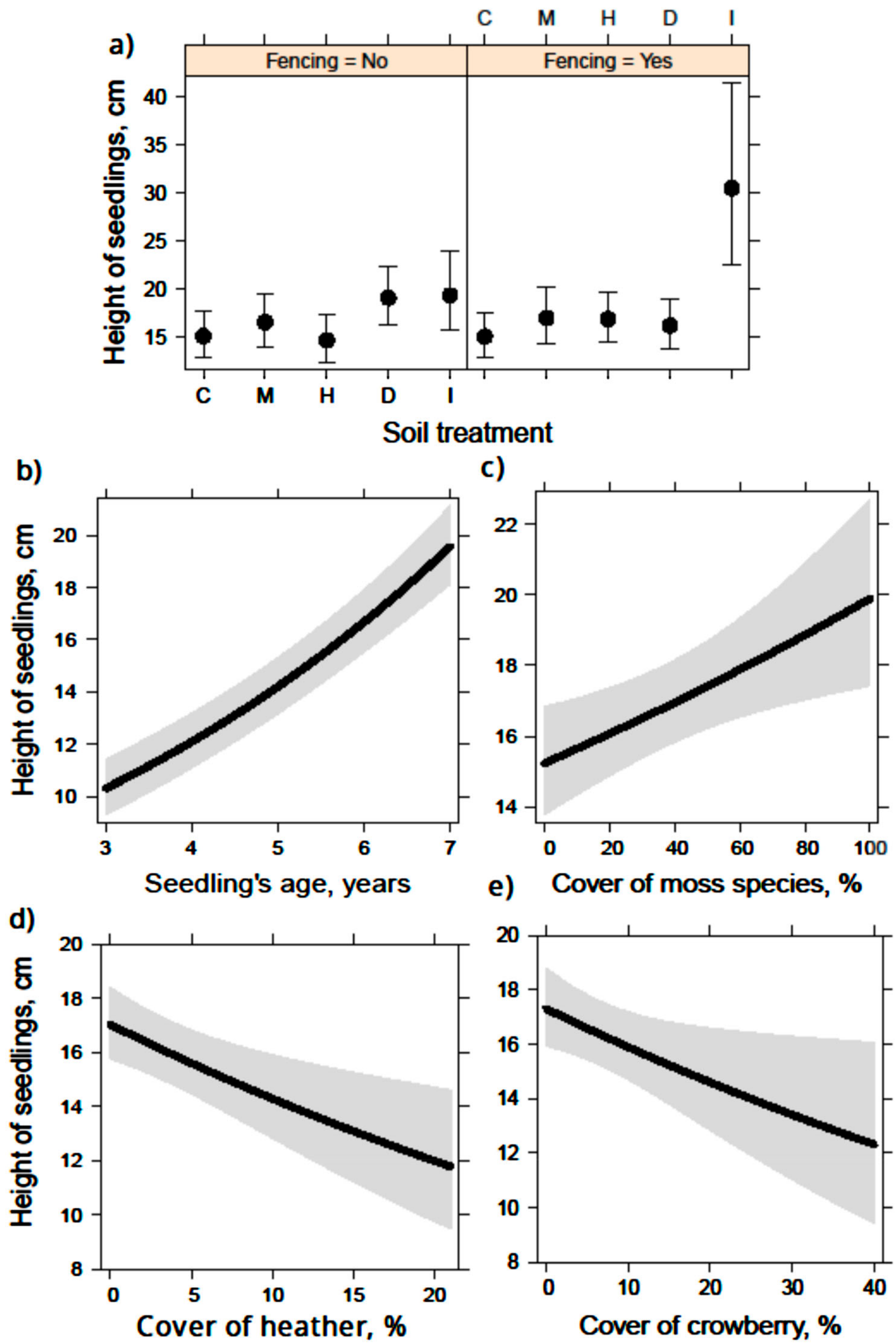

Figure 4. The prediction and their 95% confidence intervals of the height model of naturally regenerated seedlings by the interaction effect of fencing and soil treatment (a), seedling's age (b), cover of moss species (c), heather (d) and crowberry (e). Abbreviations: C = control, M = logging machine, H = Huminmix, D = disc trenching and I = intensive (> 50% of mineral soil exposed).

The increasing cover of moss, that indicates increasing site fertility, was connected to the decreasing number of seedlings. This is in accordance with earlier studies (Hallikainen et al. 2019; Kyrö et al. 2022). On the other hand, in our results increasing lichen cover as well as the abundance of heather (both of which indicate low soil fertility) was connected to the higher seedling density (Hallikainen et al. 2019). Thus, in the poorest sites, disc trenching and even Huminmix may be overly intensive site preparation methods if natural regeneration is used. This observation encourages for future studies where new type of accessories attached in harvesters and forwarders, in order to break the soil surface, would be tested to see effects in natural regeneration. Integrating wood harvesting and site preparation would significantly reduce the costs of forest management.

The height growth of naturally regenerated seedlings in all treatments was quite slow since the mean height ranged only between 15 and 30 cm at the age of 6 years. Then again, this is in line with earlier findings (Hyppönen et al. 2005; Hallikainen et al. 2007; Hyppönen and Hallikainen 2011). The combination of intensive disc trenching and fencing differed from other treatments since it led to higher height growth. This is most likely due to reduced disturbance from reindeer because the exclusion of reindeer is the only difference from the same site treatment on the non-fenced side. Our results also suggest that the potential role of field layer vegetation may be important, and in some cases complex. Heather (*Calluna Vulgaris*) may provide excellent microsites for the regeneration as we found. On the other hand, it can severely hinder the growth of pine seedlings as e.g. Norberg et al. (2001) and Hyppönen et al. (2013) have found. Thus, the role of heather may be dual, as Hyppönen et al. (2013) have argued.

Excluding reindeer had a positive effect on the number of seedlings after sowing. The difference between fenced and unfenced plots was about 10% on average. The regeneration success for seeding was rather good in all cases where any site preparation was used, in both fenced and non-fenced areas. On the most intensively treated plots fencing did not have a significant effect on the number of naturally regenerated seedlings but it increased the seedling height. On the most intensively prepared plots, the number of seedlings was so low both in fenced and non-fenced areas (<500 stems) that they would not provide a successful regeneration result in any case. Our results hence show that reindeer grazing influenced the regeneration success, as Helle and Moilanen (1993) have shown earlier. However, from the viewpoint of forestry practice it seems obvious that the site preparation has a more marked effect on the success of forest regeneration than fencing.

To conclude, our results suggest that both site preparation and reindeer grazing have effects on the natural regeneration and direct seeding of Scots pine. In natural regeneration and direct seeding even lightest site preparation methods, such as Huminmix or using logging machine tracks, may provide sufficient regeneration success. The fact that a combination of intensive site preparation (double disc trenching) and fencing led to increased height development suggests that reindeer herding limits the optimal regeneration result in the northern parts of Sweden and Finland. The use of seed pellets showed quite low survival rates, but deserves further research since it may have the potential on some occasions to reduce the consumption of seeds and the need for site preparation. These findings can help to avoid overly intensive site preparation, and this, in turn, can help to reduce the management costs. On a larger scale, the potential new paths of forest management practice presented in this study may help to reduce the confrontation between forestry and other land use forms.

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Appendix 1

Material and methods

Raw data description

The mean cover of moss species on the circle plots was 40.3% and the mean cover of lichens was 7.5%. The variation in the moss cover was large compared to the variation in the lichen cover (Figure A1.1a, 1b). The cover of exposed mineral soil varied highly depending on the soil scarification (Figure A1.1c). The heather cover was low in general but could reach the one fifth of the area of the circle plots (Figure A1.1d). Cowberries were abundant in most of the circle plots, generally covering from 5 to 10% the other soil treatment than the intensive soil scarification (Figure A1.1e). The raw distributions suggested that the sites corresponded to the sub-xeric site type, on the average. Although the cover of moss species is high, being 44% on the control plots (on the average), while there were also some xeric heather- and lichen-dominated plots in the data.

The mean number of seedlings after the three inventories (2015, 2016 and 2019, inventories together) was 4601 seedlings per ha, the median value being 1000 seedlings per ha. The number of seedlings varied a lot (Figure A1.1f) suggesting a highly aggregated seedling establishment. The development in the number of seedlings according to the inventories based on the raw data was the following (years 2015, 2016 and 2019, means, medians in the parenthesis): 3150 (1000), 4240, 6410 (2000). Thus, the number doubled over the years.

In the ground- and field-layer vegetation, the species, and the groups of the species, correlated with each other. The bottom layer consisted of moss species, lichens or exposed mineral soil or humus. Increasing cover of moss species reduced the lichen cover in many of the sample plots (Figure A1.2). The seeds sown via direct seeding (and using the seed pucks) were seeded into the mineral soil at half of the seeding points, the proportion of undisturbed vegetation being about 20%.

The relationships between the four dominating species in field-layer vegetation were weak. The strongest and statistically significant positive relationship was found between cowberries and crowberries ($t = 7.738$, df = 239, $p < 0.001$). In addition, a weaker negative relationship was found between bilberries and heather ($t = 2.217$, df = 239, $p < 0.028$). The field- and ground-layer vegetation at the seeding points were dominated by the category “no vegetation”. This denoted that the seeding points were surrounded by bare humus or exposed mineral soil. The moss species, especially *Hylocomium* and *Pleurozium* dominated the ground-layer vegetation (Figure A1.3).

Results

Seedling densities in natural regeneration

The performance and fit of the model were fairly good. The mean value was slightly overestimated: the observed mean being 5.05 and predicted being 4.80 (in 10 m^2 sample plot). Furthermore, the simulated negative

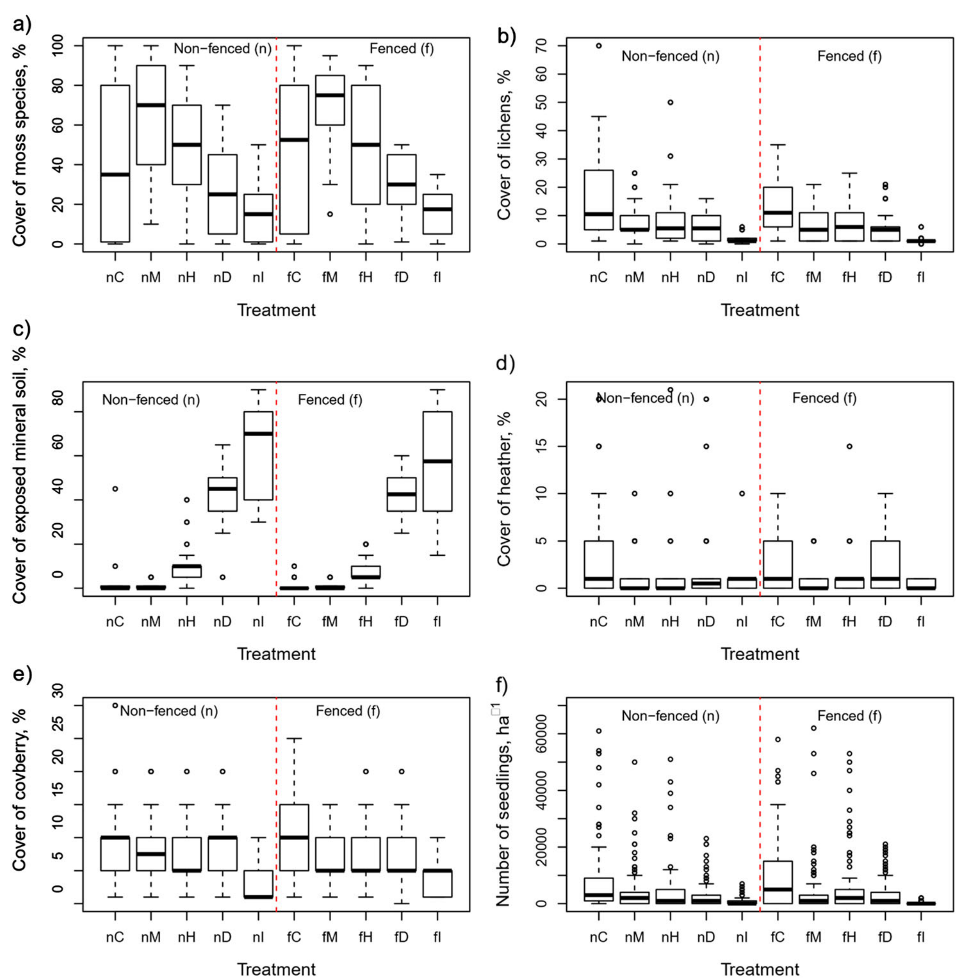

Figure A1.1. Raw distributions of moss species cover (a), lichen cover (b), exposed mineral soil (c), heather cover (d), cowberry cover (e) and the number of seedlings per ha by the treatments consisting of soil fencing and soil treatment. Abbreviations for the treatments: n denotes non-fenced, and f fenced, C denotes control, M denotes logging machine, H denotes Huminmix, D denotes disk trenching and I intensive soil scarification (> 50% exposed mineral soil). The distributions have been computed based on the circle plots (n = 300).

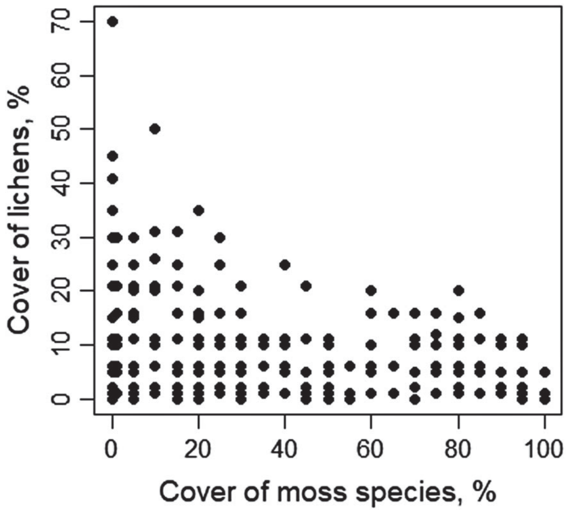

Figure A1.2. The relationship between the cover of moss and lichen species in the raw data. The relationship was significant at a 5% risk level in a mixed-effects linear model using a "quasi-Poisson" distribution (t = 5.970, df = 239, $p < 0.001$).

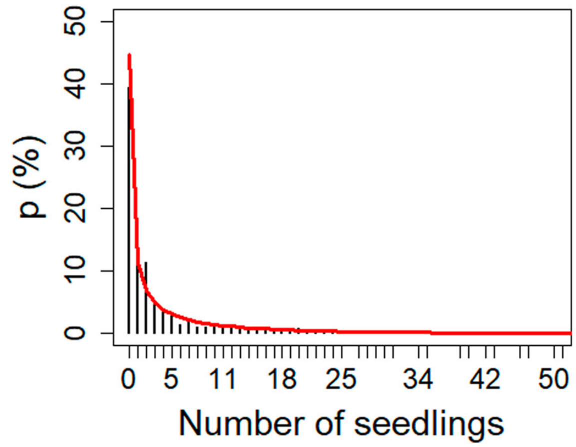

Figure A1.4. Observed and simulated probabilities of the number of seedlings on 10 m^2 sample plot using the mu = 5.03 and size = 0.27.

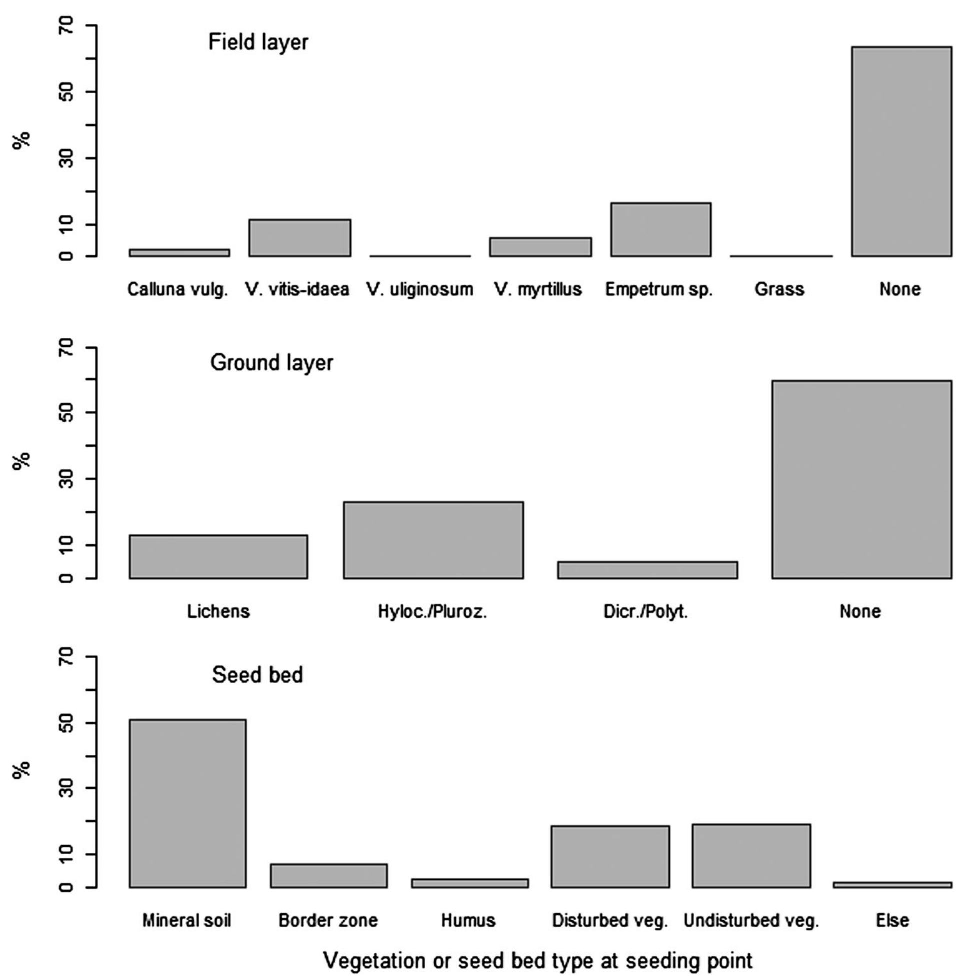

Figure A1.3. The field- and ground-layer vegetation at seeding points (radius 3 cm around the point) and the type of the seed bed based on the raw data.

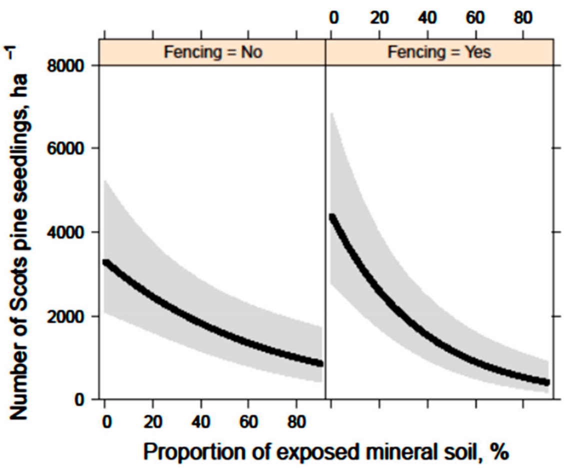

Figure A1.5. Numbers of seedlings according to mineral soil exposure percentage in fenced and non-fenced study plots.

binomial distribution using the predicted mean and theta-value of 0.27 closely followed the observed probabilities of the counts (Figure A1.4). The numbers of seedlings in natural regeneration also varied between fenced and non-fenced study plots (Figure A1.5). In general, these declined according to a mineral soil exposure percentage increase.

Height development of naturally regenerated seedlings

The fixed predictors of the model explained only 24.2% of the variation. However, the predicted (16.31 cm) and observed (16.59 cm) means of height were very close to each other. However, the model could not predict the tallest seedlings correctly (Table A1.1).

Table A1.1. The observed and predicted distributions of the seedlings' height model (cm).

	Minimum	1st quartile	Median	Mean	3st quartile	Maximum
Observed	10.00	12.00	14.00	16.59	19.00	65.00
Predicted	9.50	14.01	16.05	16.31	18.25	37.74