Predicting Establishment of Tree Seedlings in Regeneration Areas of *Picea abies* in Southern Finland

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Abstract

This study predicts the establishment of regeneration of Norway spruce (*Picea abies* (L.) Karst.) in 3-, 4- and 5-year-old regeneration areas planted, direct-seeded and naturally regenerated, respectively, in southern Finland. Establishment of regeneration was described by the number of planted, direct-seeded and natural tree seedlings, as well as by the heights of spruces and broadleaves. For each regeneration method, establishment of regeneration was modelled by fitting a multilevel multivariate model to regeneration survey data. Site and soil quality and the method of site preparation were used as explanatory variables. Stochastic simulations that accounted for the random between-stand and within-stand variation in the regeneration result were conducted to compare the uncertainty and the need for removal of broadleaves (i.e. early cleaning) involved in different methods of regeneration for spruce.

Using disc trenching as soil preparation method, the probability of good regeneration result for planting, direct seeding and natural regeneration was 58%, 34% and 38%, respectively. Using mounding, the probability of good regeneration result for planting increased to 73%. The risk of failed or poor regeneration in planting, direct seeding and natural regeneration was 3%, 37% and 32%, respectively. When considering only those simulated stands in which at least half of the plots required cleaning, 40% of planted stands, 99% of direct-seeded stands and 89% of naturally regenerated stands were deemed to require treatment. Planting was the most effective and guaranteed method of regeneration. Direct seeding and natural regeneration of spruce entail a high risk of failure.

Key words: site preparation, planting, direct seeding, stand tending, stochastic simulation

Introduction

Within sustainable forest planning, mathematical models are used to predict forest development over time. In forest simulators, regeneration or ingrowth models are linked with the growth models of overstory trees to predict the dynamics of stand regeneration and development (e.g. Ferguson and Carlson 1993, Hynynen et al. 2002). In silvicultural planning, models are used to predict establishment of tree seedlings for comparing methods of forest regeneration (e.g. Pukkala and Kolström 1992, Pacala et al. 1996, Miina and Saksa 2008, Kankaanhuhta et al. 2009, Li et al. 2011). Tree regeneration is a highly variable and stochastic process derived from soil and weather conditions, competition by overstory trees and ground vegetation, etc. This makes predicting establishment and development of regeneration more challenging.

Intensive forestry with clear-cutting and planting has been seen to cause negative effects on the ecological, aesthetic and recreational aspects of forests. To fulfill goals other than timber production or economic profitability, changes in silviculture and management are being invoked in Finnish forestry. For example, natural regeneration for spruce is attracting increasing interest in Finland. Natural regeneration and direct seeding of Norway spruce (*Picea abies* (L.) Karst.) are rarely used, since planting is considered more guaranteed. For example, the timing with a good seed year is essential for successful natural regeneration due to fast invasion of ground vegetation species. The most frequently used methods for natural regeneration of spruce are shelterwood cuttings without soil preparation or to make small clear-cuts, prepare the soil, and then leave the area to natural seeding from stands nearby. In privately owned forests regenerated for spruce in 2011 (about 40,000 ha in total), 95% was planted, < 1% direct-seeded and 5% naturally regenerated (Metsätalouden kehittämiskeskus Tapio 2011).

According to Karppinen (2005), the values and objectives of forest owners affect the selection of regeneration method. Forest owners could be encouraged to make better decisions by offering more information on the possible outcomes and especially risks of different methods of regeneration. Such estimates for distributions of the outcomes of regeneration methods applied in practice could be determined by regeneration surveys and experiments (e.g. Ackzell 1993, Hyppönen et al. 2005, Nilsson et al. 2006, Saksa and Kankaanhuhta 2007). Ahtikoski et al. (2010) assessed the combined effect of uncertainty related to regeneration success and establishment costs on experiment plots, and compared alternative regeneration methods for Scots pine (*Pinus sylvestris* L.) in northern Finland. Most preferably such comparisons should cover the whole rotation period of the established stand, not only the regeneration phase. Zhou (1999) and Hyytiäinen et al. (2006) combined empirical data on regeneration success, a forest growth model, and stand-level economic optimization to investigate financial returns from investments for establishing Scots pine stands in Sweden and Finland, respectively. Both ecological and economical information on regeneration methods will help forest owners to select the method that best fits the specific site and objectives.

The aims of this study were to construct and evaluate models of regeneration establishment and compare different methods of regeneration for Norway spruce (*Picea abies* (L.) Karst.) in southern Finland. For example, the effects of site condition and soil preparation variables on the establishment of tree seedlings on planted, direct-seeded and naturally regenerated areas were evaluated. Stochastic simulations were conducted, as reported by Miina and Heinonen (2008), to compare the distributions of outcomes of regeneration methods as well as the need for, and costs of removal of broadleaves. Especially the probabilities of succeeding and failing in planting, direct seeding and natural regeneration were compared. The work is an extension of previous work by the authors in which a similar model was developed for planted spruce only (Miina and Saksa 2006) and for planted, direct-seeded and naturally regenerated Scots pine (Miina and Saksa 2008). In this study, a more comprehensive data set was used for planted spruce, and also direct seeding and natural regeneration for spruce were analyzed.

Materials and Methods

Field sampling in regeneration survey

Modelling the establishment of regeneration was based on the database for a regeneration survey in southern Finland (Saksa and Kankaanhuhta 2007). Privately owned forest areas planted, direct-seeded and naturally regenerated were surveyed at the age of 3, 4 and 5 years, respectively. At this stage, the result from the regeneration activities could already be seen but seedlings had not yet suffered from competition by broadleaves. During 2000–2006, data on establishment of regeneration were collected in six forestry centres scattered throughout southern Finland (Kankaanhuhta et al. 2009). Forest management associations (FMAs) located within those forestry centres and willing to participate in the project were included in the survey. Because an FMA covers one or several municipalities, the geographical unit was the municipality. Within a municipality all regeneration areas of the given ages that were larger than 0.5 ha were assessed.

The following historical information was registered from official records and checked in the field for regeneration areas: forestry centre, municipality, year of regeneration cutting, year of site preparation, year of planting or direct seeding, total area of the regenerated stand, seedling material and executor of regeneration (forest owner or FMA). The need for silvicultural treatments was also determined. To describe the large-scale variation in site conditions and the location of the regeneration area, the municipality-level values of altitude and the mean effective temperature sum (lower threshold +5°C) estimated from the measurements for the period 1971–2000 made by the Finnish Meteorological Office were added to the data (Ojansuu and Henttonen 1983). To depict the proportional coverage of lakes and sea within a radius of 20 km, the respective municipality-level lake and sea indices were calculated.

In each regeneration area, establishment of regeneration was measured systematically on 15–20 temporary sample plots (20 m^2), depending on the size of the regeneration area. Site characteristics, method of site preparation (no preparation, patch scarification, hereafter patching, disc trenching or mounding), target-tree species and regeneration method were determined for each plot. The following site characteristics were determined: whether stony or wet soil has affected regeneration or not, site fertility and soil texture class (coarse, medium or fine mineral soil, or peat if the peat layer was thicker than 20 cm). The fertility of mineral soils was determined using the following site-type classification (Cajander 1926): *Oxalis–Maianthemum* type (OMaT), *Oxalis–Myrtillus* type (OMT), *Myrtillus* type (MT), *Vaccinium* type (VT), *Calluna* type (CT) and *Cladonia* type (ClT). The fertility of peatlands was determined using the same main classes (Laine and Vasander 2005).

On the plot, established seedlings were assessed by counting the number of healthy planted seedlings, natural and direct-seeded spruces, natural pines, seed-origin birches and other broadleaves, i.e. sprout-origin birches and deciduous tree species other than birch (Table 1). A healthy seedling had no damage that would affect its future vigour and survival. Natural and direct-seeded seedlings were counted if they were healthy and at least 5 cm tall, and the distance between the counted seedlings was more than 30 cm. The maximum number of seedlings per plot and per tree species was set at 20 (i.e. the number of seedlings was right-censored to 20 seedlings per plot). Planted and natural spruces were distinguished by their age, substrate and location (i.e. 1- or 2-year-old seedlings were planted into a well prepared soil). Because it was not possible to distinguish between natural and direct-seeded spruces, seeded spruces are later used to refer to both direct-seeded and natural spruces in direct-seeded stands. The height of the crop-tree spruce closest to the centre of the plot and the dominant height of broadleaves (i.e. the height of the tallest deciduous tree) were measured to the nearest 5 and 10 cm, respectively.

In planted stands, natural crop trees were selected such that they supplemented planted spruces. Crop trees were assumed to reach merchantable stem size at the time of the first commercial thinning. In 3-year-old planted conifer stands, only pines and spruces were accepted as crop trees. In direct-seeded and naturally regenerated areas, crop trees were not determined. Natural crop trees were counted if their height was at least half the height of planted seedlings, and the distance between the crop trees was more than 1 m. The maximum number of crop trees was set at six seedlings per plot (equals 3,000 ha^{-1}). Later on, crop trees are used to refer to both planted spruces and natural crop-tree conifers in planted stands.

The data set collected from planted Norway spruce in 2000–2002 has earlier been used in developing the modelling (Miina and Saksa 2006) and simulation approach (Miina and Heinonen 2008). Therefore, in this study, regeneration areas surveyed in 2003–2005 were included in the modelling data sets for planting of Norway spruce. In addition, regeneration areas surveyed in 2000–2005 were included in the modelling data sets for direct seeding and natural regeneration of Norway spruce. As the regeneration method and target tree species may vary within a regeneration area, only regeneration areas with at least ten sample plots on which the regeneration method was planting, direct seeding or natural regeneration of Norway spruce were included in the modelling data sets. All models were validated using the data sets collected in 2006. Only regeneration areas with at least ten sample plots on which the regeneration method was planting were included in the validation data set. Due to a lower number of direct-seeded and naturally regenerated areas, regeneration areas with at least three sample plots were included in the corresponding validation data sets.

In the modelling data sets, there were in total 38,265, 1,931 and 2,698 sample plots on 2,455 planted areas, 119 direct-seeded areas and 175 naturally regenerated areas, respectively (Table 1). These planted, direct-seeded and naturally regenerated areas were surveyed in 84, 18 and 33 municipalities, respectively, located within six forestry centres. In the validation data sets collected in 2006, there were in total 20,805, 177 and 80 sample plots on 1310 planted areas (26 municipalities, six forestry centres), 14 direct-seeded areas (five municipalities, four forestry centres) and 13 naturally regenerated areas (five municipalities, three forestry centres), respectively.

Table 1. The main characteristics of the modelling data sets for planting, direct seeding and natural regeneration for Norway spruce

	Planting					Direct seeding					Natural regeneration				
Variable	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
n_1	38265	2.80	1.52	0	9	--	--	--	--	--	--	--	--	--	--
n_2	38265	0.24	0.65	0	6	--	--	--	--	--	--	--	--	--	--
n_3	38265	0.38	0.86	0	6	--	--	--	--	--	--	--	--	--	--
n_4	38265	0.65	1.78	0	20	1931	1.53	2.36	0	20	2698	1.13	2.83	0	20
n_5	38265	3.79	3.01	0	20	1931	4.47	5.27	0	20	2698	5.88	5.96	0	20
n_6	38265	5.92	6.70	0	20	1931	9.69	7.54	0	20	2698	4.00	5.68	0	20
n_7	38265	7.44	6.27	0	20	1931	8.21	6.39	0	20	2698	7.44	6.36	0	20
h_1	36089	56.5	19.6	5	400	1467	29.2	30.5	5	400	2251	65.7	60.9	5	700
h_2	34358	120.6	53.8	10	800	1771	130.5	53.7	10	450	2407	156.7	85.2	10	800
Area	2455	1.9	1.5	0.5	21.3	119	2.2	1.5	0.5	7.4	175	1.8	1.8	0.5	13.7
Lake	84	8.1	10.3	0.0	41.5	18	13.9	11.0	0.0	37.1	33	12.0	12.3	0.0	41.5
Sea	84	2.5	7.5	0.0	49.2	18	0.0	0.0	0.0	0.0	33	0.6	2.9	0.0	16.4
Alt	84	81.2	42.9	10	173	18	108.6	31.7	51	171	33	89.0	38.0	22	155
Ts	84	1206.0	79.4	1017	1334	18	1142.2	64.0	1044	1241	33	1186.0	77.3	1049	1329

Note: *N* = number of observations at the plot, stand or municipality level; $n_1 – n_7$ = number of planted pines, natural crop-tree pines and spruces, natural pines, natural spruces, seed-origin birches and other broadleaves on 20 m^2 plots, respectively; h_1 and h_2 = height (cm) of spruces and dominant height (cm) of broadleaves, respectively; *Area* = regeneration area (ha); *Lake* = lake index (%); *Sea* = sea index (%); *Alt* = altitude (m); *Ts* = temperature sum (d.d.).

There were only slight differences in site type between the data sets for different methods of regeneration (Table 2). On about 70–80% of sample plots, site fertility was medium (MT) and on about 15–25% rich (OMaT or OMT). Only on 3–5% of sample plots, site fertility was poor (VT, CT or ClT). The main difference between the data sets was in the site preparation. On planted areas, patching (40% of sample plots), disc trenching (35%) and mounding (22%) were commonly used. On direct-seeded areas, patching was the most common method of site preparation (63% of sample plots), the rest of the sample plots were disc trenched (28%) and mounded (10%). On natural regeneration areas, the soil was not prepared on 57% of the sample plots.

Table 2. Number of sample plots summarized by site preparation method and site type in the modelling data sets

	Site preparation					
Site type	No preparation	Disc trenching	Patching	Mounding	Total	(%)
Planting						
OMaT or OMT	312	2840	4487	1977	9616	(25.1)
MT	913	9835	10317	6016	27081	(70.8)
VT or CT	70	686	479	333	1568	(5.1)
Total (%)	1295 (3.4)	13361 (34.9)	15283 (40.0)	8326 (21.8)	38265 (100.0)	(100.0)
Direct seeding						
OMaT or OMT	21	111	137	9	278	(14.4)
MT	18	422	1022	126	1588	(82.2)
VT or CT	0	4	56	5	65	(3.4)
Total (%)	39 (2.0)	537 (27.8)	1215 (62.9)	140 (7.3)	1931 (100.0)	(100.0)
Natural regeneration						
OMaT or OMT	256	218	140	17	631	(23.4)
MT	1180	371	356	30	1937	(71.8)
VT or CT	105	6	19	0	130	(4.8)
Total (%)	1541 (57.1)	595 (22.1)	515 (19.1)	47 (1.7)	2698 (100.0)	(100.0)

Note: OMaT = *Oxalis–Maianthemum* type; OMT = *Oxalis–Myrtillus* type; MT = *Myrtillus* type; VT = *Vaccinium* type; CT = *Calluna* type.

Modelling the establishment of regeneration

The establishment of regeneration was modelled by fitting a multilevel multivariate model for each regeneration method (e.g. Goldstein 2003). The model for planting consisted of nine submodels for the numbers of trees in seven tree species classes and for the heights of spruces and broadleaves. Because numbers of natural crop trees were determined only for planted stands, the models for direct seeding and natural regeneration consisted of six submodels: four for the numbers of seedlings and two for measures of height.

The numbers of seedlings were modelled by fitting extra-Poisson multilevel models:

$$n_{lkji} \sim \text{Poisson}(\mu_{lkji})$$
$$\mu_{lkji} = \exp\{f(X_{lkji}, \beta) + u_l + u_{lk} + u_{lkj}\} \quad (1)$$

where n_{lkji} is the number of seedlings in tree species class on plot *lkji*, the conditional distribution of n_{lkji}, given the expected value μ_{lkji}, is a Poisson distribution; $f(\cdot)$ is the fixed part of the model; X_{lkji} is a vector of fixed predictors; and β is a vector of fixed parameters. Subscripts i, j, k and l refer to plot i, regeneration area (later referred as stand) j, municipality k and forestry centre l, respectively. The u_l, u_{lk} and u_{lkj} are random, normally distributed between-forestry centre, between-municipality and between-stand effects with a mean of 0 and constant variances. Note that the plot-level random errors of the Poisson model are defined as the deviations between random realizations and conditional plot means. Because seedlings are not randomly distributed over the regeneration area, the number of trees was allowed to be under- or overdispersed relative to the Poisson law. Extra-Poisson variation was obtained by assuming that the conditional variance is proportional to the mean: $\text{var}(n_{lkji}) = \Phi \times \mu_{lkji}$, where Φ is a constant known as the dispersion parameter.

The tree heights were square-root transformed and modelled by fitting normal multilevel models:

$$\sqrt{h_{lkji}} = f(X_{lkji}, \beta) + u_l + u_{lk} + u_{lkj} + e_{lkji} \quad (2)$$

where h_{lkji} is the height of the crop-tree spruce or the dominant height of broadleaves (cm), and e_{lkji} is a normally distributed error term at the plot level with a mean of 0 and constant variance.

The fixed predictors such as temperature sum, altitude, lake and sea indices and the size of the regeneration area were considered in the models. Seedling material, executor of regeneration, site fertility, soil characteristics and method of site preparation were categorical predictors and included using dummy variables (1 or 0). When the dummy variables were formed, a common regeneration situation of Norway spruce was selected as the basis of the models, e.g. medium site fertility (MT), medium mineral soil texture and disc trenching. All the fixed predictors included in the models had to be logical and significant at the 0.05 level.

Owing to the hierarchical structure of the data and the simultaneous determination of the extent and composition of regeneration, multivariate multilevel modelling was applied (Goldstein 2003). Correlation of plot-level outcomes of an individual response variable was taken into account by random effects at different levels (Searle et al. 1992). In addition, the random effects and errors of the submodels were assumed to be cross-correlated at the same level but uncorrelated across levels. The submodels were fitted simultaneously by the use of MLwiN software and application of a combination of the iterative generalized least-squares (IGLS) and the first order marginal quasi-likelihood (MQL) procedures (Rasbash et al. 2005).

Model evaluation

The performance of the individual submodels was examined by predicting the establishment of regeneration for both the modelling and validation data sets using the fixed part of each submodel, and the mean error (E), mean absolute error ($|E|$) and mean squared error (E^2) were calculated as follows:

$$
\begin{aligned}
E &= \sum (y_i - \hat{y}_i)/N \\
|E| &= \sum |y_i - \hat{y}_i|/N \\
E^2 &= \sum (y_i - \hat{y}_i)^2/N
\end{aligned}
\tag{3}
$$

where y_i and $\hat{y}_i$ are measured and predicted responses, respectively, and N is the number of observations. The statistical significance of the mean error was assessed using a two-tailed t test. In addition, the relative mean error was calculated by dividing the mean error by the mean of the measured response. For the Poisson models (eq. 1), the Pearson residuals $(y_i - \hat{y}_i)/\sqrt{\Phi \times \hat{y}_i}$ were calculated for the error statistics (McCullagh and Nelder 1989). The square-root transformed tree heights were back-transformed to the original scale before the error statistics were calculated, i.e. the total residual variance was added to the squared prediction.

Stochastic simulations

The simulation method applied in this study has been described in detail by Miina and Heinonen (2008). The establishment of seedlings was stochastically simulated by first predicting the numbers and heights of trees using only the fixed part of each model and then adding realizations of the random between-stand effects and random errors to the predictions. Stochastic variation at the forestry centre and municipality level was not simulated. At the stand level, plot-level expectations of the response variables were calculated so that truncated random stand-level effects were simulated (± 5×SD(u_{lkj}) to reject small and large values) and added to the linear predictions of eqs. 1 and 2. At the plot level, the model defines the means and variances of the response variables, but it does not specify entire distributions. The underdispersed count variable was assumed to have a binomial distribution, the overdispersed ones a negative binomial distribution and the square root of the height variables a normal distribution. The joint distribution of the response variables was defined by a multivariate normal (MVN) copula (Nelsen 2006), and a sample from an MVN distribution was transformed to a sample from the joint distribution (target distribution). Finally, the predicted counts were right-censored to 20 and the square roots of the height variables were squared.

We simulated the establishment of seedlings for a common regeneration situation of Norway spruce: a disc-trenched site of medium fertility (*Myrtillus* type) and medium soil texture. A temperature sum of 1,250 d.d., altitude 100 m, sea index of 0% and lake index 15% were used as predictors. In planting, the establishment of seedlings was simulated also for a mounded site. Within a stand, 20 sample plots were simulated. The establishment of seedlings for the planted, direct-seeded and naturally regenerated spruce stand was predicted 1,000 times, i.e. 1,000 stands and 20,000 plots were simulated. The simulation was programmed and the random numbers were generated in the R-environment (R Development Core Team 2013).

The probabilities of obtaining a given number of seedlings ha^{-1} were calculated using the simulated outcomes. Since direct-seeded and natural seedlings are clustered on the regeneration area, the greater threshold for numbers of seedlings ha^{-1} is assumed to give the equivalent regeneration result to that of the regularly-spaced planted seedlings. In addition, the minimum distance between the counted crop trees and natural/seeded seedlings was 1 m and 30 cm, respectively. Similar to the study of Saksa and Kankaanhuhta (2007), the regeneration result for planting was considered to be poor, moderate or good if the number of crop trees was at least 800, 1,200 or 1,600 ha^{-1}, respectively. In direct seeding and natural regeneration, minimum threshold density values of 1,000, 2,000 and 3,000 spruces ha^{-1} were used for a poor, moderate and good regeneration result, respectively. The regeneration result was classified as failure if the number of crop trees in planting was < 800 ha^{-1} and the number of spruces in direct seeding and natural regeneration was < 1,000 ha^{-1}. Note that on the plot level (20 m^2), each seedling represents 500 trees ha^{-1}, and thus the densities 0, 500, 1,000, etc. trees ha^{-1} were used in classification.

As in practical forestry, the density and height of crop trees and deciduous tree species were used to determine the need for removal of undesired broadleaves (i.e. early cleaning) of the simulated stands (cf.

Kiljunen 2004, Uotila et al. 2012). The need for cleaning was determined first for each plot and then for each stand as follows. On the planted plots with ≥ 1,500 crop trees ha^{-1} and on the direct-seeded and naturally regenerated plots with ≥ 2,000 spruces ha^{-1}, cleaning was needed if the number and dominant height of broadleaves (i.e. seed-origin birches and other broadleaves) were, respectively, > 2,000 trees ha^{-1} and > 50% higher than the height of spruces. On poorly regenerated plots (i.e. < 1,500 crop trees ha^{-1} or < 2,000 spruces ha^{-1}), small natural conifers are used to supplement crop trees, and thus cleaning was needed if the number and dominant height of broadleaves were > 1,000 trees ha^{-1} and > 0.75 m (planted) or 0.5 m (direct-seeded and natural), respectively. The stand was cleaned if at least half of the plots within the stand needed it. The cleaning costs of the stand were the average cleaning costs of the plots within the stand. If there were no broadleaves on the plot, the cleaning costs of the plot were 0. Otherwise, according to the pricing guide for precommercial thinning of saplings stands in Finland (Anon. 2008), the cleaning costs were calculated as a function of the mean diameter at stump height and number of broadleaves on the plot. The mean diameter at stump height (cm) of broadleaves was calculated as a function of dominant height of broadleaves (h_2, cm) as follows: $d = -1.51 + 0.015 \times \max(130, h_2)$.

Results

Regeneration models

The variables describing the location of the regeneration area (temperature sum, altitude and lake index) affected establishment of seedlings only slightly (Tables 3–5). In the submodels for the height of crop-tree spruces in artificially regenerated stands, the coefficient of temperature sum was positive, i.e. the crop-tree spruces were taller in south than in north. In the submodel for the dominant height of broadleaves on naturally regenerated areas, the coefficient of temperature sum was negative and may not describe a causal effect of temperature sum *per se*, which would be contrary to established knowledge of temperature effects on height increment (e.g. Hynynen et al. 2002), but is probably related to differences in the structure of naturally regenerated stands within the study area. The lake index had a positive effect on the number of natural and direct-seeded spruces, i.e. there were more spruce seedlings in the lake districts in south-eastern Finland than in western Finland.

The wetness and fine mineral soil, as well as peat soil decreased the number of conifer seedlings, and increased the number of broadleaves. On rich sites (OMaT and OMT), there were fewer spruce seedlings than on medium sites (MT). The number of pines was greatest on the poorest sites (VT and CT).

When analyzing the effect of soil preparation on establishment of seedlings, it should be noted that the parts of the regeneration area with good advance regeneration may not have been prepared at all, and only supplementary planting was done. This was supported by the result that there were more natural crop-tree spruces on unprepared plots than on prepared plots. If the soil was not prepared in the area of the sample plot, the number of planted spruces decreased by 9% and the number of natural crop-tree spruces increased by 39%. The mounding was the best method of soil preparation with a 9% increase in the number of planted spruces. On direct-seeded areas, the method of soil preparation had no effect on the establishment of spruce seedlings; probably the plots with advance spruce regeneration have not been prepared or direct-seeded. On naturally regenerated areas, patching and mounding increased the number of spruces by 42% and 59%, respectively, compared to unprepared and disc-trenched plots. In planted and naturally regenerated areas, there were about 40% fewer seed-origin birches on unprepared plots than on prepared plots. In general, patching exposes more mineral soil and thus resulted in more natural seedlings than disc trenching.

If planting work was carried out by FMA (on 50% of the plots), there were 3% more planted spruces on the plots. On naturally regenerated areas, there were 21% more spruce seedlings, if forest regeneration activities were carried out by FMA (on 50% of the plots). The use of bare-root seedlings (on 7% of the plots) increased the number of planted spruces by 4%.

Natural crop-tree spruces supplemented the planted spruces especially on wet and peat soils and unprepared plots, while the number of natural crop-tree pines on poor sites was high. On rich sites (OMaT and OMT), the numbers of natural seedlings were low, and thus they supplemented planted seedlings less often than on medium sites (MT).

The variance components of the models were high, i.e. the predictors of the fixed part did not explain the variation in regeneration establishment very well (Tables 3–5). All random effects at the forestry centre level, as well as the random municipality-level effects of the models for direct seeding and natural regeneration were not significant, and they were therefore set at zero in the submodels. In the submodels for planting, correlations among the random municipality-level effects were also non-significant and set at zero. As expected, the estimated dispersion parameter for the number of planted spruces was less than 1 (0.74), because seedlings are planted as evenly as possible. The natural crop-tree pines were almost randomly distributed (dispersion was 1.48), but other natural seedlings and seeded spruces were more clustered on the regeneration area (dispersion was 1.95–5.24).

Table 3. Parameter estimates and variance components (approximate SE in parentheses) of the regeneration model for spruce planting

Predictor	n_1	n_2	n_3	n_4	n_5	n_6	n_7	h_1	h_2
Intercept	0.9864	-1.2499	-1.0600	-4.5871	1.2051	1.7334	1.9399	-2.1207	9.9355
	(0.0210)	(0.0739)	(0.0669)	(1.1424)	(0.0335)	(0.0568)	(0.0386)	(1.1869)	(0.1686)
Lake index (%)	0.0041	–	–	–	0.0077	–	–	0.0108	0.0324
	(0.0013)				(0.0021)			(0.0046)	(0.0113)
Altitude (m)	–	–	–	–	–	–	–	0.0082	–
								(0.0018)	
Temperature sum (100 d.d.)	–	–	–	0.3552	–	–	–	0.7302	–
				(0.0955)				(0.0899)	
Stony soil	-0.3332	-0.2602	0.1917	-0.3712	-0.3117	-0.2971	–	-0.1548	–
	(0.0189)	(0.0842)	(0.0678)	(0.0975)	(0.0270)	(0.0346)		(0.0372)	
Wet soil	-0.3761	0.2715	0.4589	–	-0.2219	0.4729	0.1417	-0.4730	-0.4396
	(0.0225)	(0.0788)	(0.0680)		(0.0299)	(0.0297)	(0.0259)	(0.0440)	(0.0775)
OMaT	-0.0238	-1.7082	-0.3814	-1.3877	-0.1445	-0.3435	0.3064	0.3231	1.3161
	(0.0305)	(0.0788)	(0.1578)	(0.2904)	(0.0463)	(0.0636)	(0.0401)	(0.0681)	(0.1233)
OMT	-0.0401	-0.8809	-0.1412	-0.7336	-0.0687	-0.1757	0.1092	0.2121	0.6146
	(0.0075)	(0.0462)	(0.0345)	(0.0492)	(0.0109)	(0.0142)	(0.0109)	(0.0168)	(0.0309)
VT or CT	-0.0817	0.8126	–	0.7310	-0.0914	-0.1044	-0.0714	-0.1601	-0.3514
	(0.0145)	(0.0479)		(0.0549)	(0.0210)	(0.0272)	(0.0222)	(0.0327)	(0.0597)
Coarse mineral soil	–	–	–	–	–	-0.0788	–	–	-0.3827
						(0.0286)			(0.0620)
Fine mineral soil	-0.0340	-0.1461	–	-0.2201	-0.0593	0.0684	0.0602	-0.0547	0.2302
	(0.0067)	(0.0336)		(0.0378)	(0.0096)	(0.0126)	(0.0099)	(0.0151)	(0.0281)
Peat soil	-0.0565	–	0.2689	–	–	0.2433	0.0650	-0.1511	0.2746
	(0.0107)		(0.0492)			(0.0210)	(0.0183)	(0.0281)	(0.0533)
No site preparation	-0.0896	-0.8946	0.3259	-1.0081	–	-0.4796	–	–	–
	(0.0137)	(0.1108)	(0.0606)	(0.1309)		(0.0368)			
Patching	–	–	–	0.2129	0.0442	0.0787	–	–	–
				(0.0358)	(0.0084)	(0.0146)			
Mounding	0.0841	–	–	–	0.1170	0.1853	–	–	–
	(0.0071)				(0.0109)	(0.0155)			
Mounding and wet soil	–	–	–	–	–	-0.6532	–	–	–
						(0.1047)			
Executed by FMA	0.0319	–	–	–	–	–	–	–	–
	(0.0045)								
Bareroot seedlings	0.0399	–	–	–	–	–	–	–	–
	(0.0088)								
var(u_{lk})	0.0066	0.1879	0.2216	0.1657	0.0217	0.1693	0.0767	0.1142	0.7532
	(0.0023)	(0.0592)	(0.0539)	(0.0628)	(0.0061)	(0.0397)	(0.0183)	(0.0277)	(0.1933)
var(u_{lkj})	0.0244	0.4917	0.2112	0.6180	0.0542	0.1788	0.0873	0.1308	1.1560
	(0.0027)	(0.0571)	(0.0288)	(0.0716)	(0.0060)	(0.0194)	(0.0097)	(0.0152)	(0.1216)
ϕ or var(e_{lkji})	0.7447	1.4821	1.9503	4.4193	2.0563	5.2422	4.2672	1.2540	4.1020
	(0.0054)	(0.0108)	(0.0141)	(0.0321)	(0.0149)	(0.0380)	(0.0310)	(0.0094)	(0.0314)

Note: the predicted variables are the number of planted spruces (n_1), natural crop-tree pines (n_2) and spruces (n_3), natural pines (n_4), natural spruces (n_5), seed-origin birches (n_6) and other broadleaves (n_7) on 20 m^2 plots (eq. 1), and the height (cm) of spruces (h_1) and dominant height (cm) of broadleaves (h_2) (eq. 2).
For class variables (i.e. unit not given), if the value is true, 1; otherwise, 0.
OMaT = *Oxalis–Maianthemum* type; OMT = *Oxalis–Myrtillus* type; MT = *Myrtillus* type; VT = *Vaccinium* type; CT = *Calluna* type; FMA = forest management association.

All statistically significant correlations among the random effects and random errors were logical and shared mostly the same sign at the stand and plot levels (Table 6). The random effects of the submodel for the number of planted spruces correlated negatively (correlations -0.13 – -0.30) with those for the number of natural crop-tree conifers that supplement the planted seedlings. Meanwhile, the random effects of the submodel for the number of planted spruces correlated positively with those for the number of other natural spruces both at the stand level (0.73) and plot level (0.56). In all three models, the random effects of the height submodels were positively correlated, especially at stand level. This is suggesting that the growing conditions on the stand have affected the growth of spruces and broadleaves similarly.

The models gave slightly positively or negatively biased predictions for the number of seedlings in the data sets used for modelling and validation (Table 7). In the modelling data sets, the submodels for tree heights were usually unbiased but gave overestimations in the validation data sets. In the validation data set, the mean squared errors (E^2) were at the same level as in the modelling data set. The root mean squared errors (RMSE) of the count models were about

Table 4. Parameter estimates and variance components (approximate SE in parentheses) of the regeneration model for spruce direct seeding

Predictor	n_4	n_5	n_6	n_7	h_1	h_2
Intercept	0.2921 (0.1414)	1.1536 (0.1480)	4.8205 (1.3219)	2.0616 (0.0655)	-5.0905 (3.2296)	10.4933 (0.3358)
Lake index (%)	–	0.0445 (0.0112)	–	–	–	0.0949 (0.0245)
Temperature sum (100 d.d.)	–	–	-0.2425 (0.1195)	–	0.9357 (0.2932)	–
Stony soil	-0.5630 (0.2166)	–	-0.3288 (0.0878)	–	0.4831 (0.2313)	–
Wet soil	–	-0.4320 (0.2083)	0.2987 (0.0961)	–	–	–
OMaT or OMT	-0.8772 (0.1638)	-0.4726 (0.0818)	-0.3995 (0.0558)	–	–	–
VT or CT	0.6373 (0.1700)	–	–	–	–	–
Coarse mineral soil	–	0.6297 (0.1530)	–	–	–	–
Fine mineral soil	-0.3166 (0.0988)	-0.1478 (0.0634)	0.1231 (0.0388)	–	–	-0.3211 (0.1072)
Peat soil	–	–	0.1804 (0.0683)	0.1980 (0.0674)	–	–
Patching	0.2651 (0.1197)	–	0.1190 (0.0437)	–	–	–
Mounding	0.5247 (0.1730)	–	–	–	–	–
var(u_{lkj})	0.4721 (0.1209)	0.3231 (0.0762)	0.1674 (0.0393)	0.1704 (0.0405)	1.2469 (0.3022)	2.1047 (0.4796)
ϕ or var(e_{lkji})	3.5660 (0.1161)	4.1902 (0.1364)	4.1728 (0.1359)	4.1674 (0.1357)	3.2703 (0.1226)	3.5684 (0.1213)

Note: the predicted variables are the number of natural pines (n_4), seeded and natural spruces (n_5), seed-origin birches (n_6) and other broadleaves (n_7) on 20 m^2 plots (eq. 1), and the height (cm) of spruces (h_1) and dominant height (cm) of broadleaves (h_2) (eq. 2).
For class variables (i.e. unit not given), if the value is true, 1; otherwise, 0.
OMaT = *Oxalis–Maianthemum* type; OMT = *Oxalis–Myrtillus* type; MT = *Myrtillus* type; VT = *Vaccinium* type; CT = *Calluna* type

Table 5. Parameter estimates and variance components (approximate SE in parentheses) of the regeneration model for spruce natural regeneration

Predictor	n_4	n_5	n_6	n_7	h_1	h_2
Intercept	0.2635 (0.1587)	1.4453 (0.1000)	1.6533 (0.1210)	1.9300 (0.0703)	7.0588 (0.2238)	18.3305 (3.0666)
Lake index (%)	–	0.0173 (0.0052)	–	–	–	0.0361 (0.0145)
Temperature sum (100 d.d.)	–	–	–	–	–	-0.5940 (0.2558)
Stony soil	-0.7094 (0.3084)	-0.3796 (0.1577)	–	–	–	–
Wet soil	–	–	0.2431 (0.1210)	–	–	–
OMaT or OMT	-0.7078 (0.1163)	-0.1952 (0.0489)	-0.4431 (0.0660)	0.1136 (0.0396)	0.6717 (0.1662)	1.0425 (0.1620)
VT or CT	0.8323 (0.1098)	–	–	-0.3140 (0.0788)	–	-0.5762 (0.2842)
Coarse mineral soil	–	–	-0.4865 (0.1597)	–	–	–
Fine mineral soil	-0.5893 (0.0924)	–	0.2206 (0.0554)	–	0.6898 (0.1471)	0.2922 (0.1426)
Peat soil	–	–	0.4292 (0.0869)	–	0.7151 (0.2395)	1.1848 (0.2425)
No site preparation	–	–	-0.4913 (0.0770)	–	–	–
Patching	0.6347 (0.1213)	0.3536 (0.0565)	–	0.2144 (0.0490)	–	–
Mounding	–	0.4610 (0.1415)	–	–	–	–
Executed by FMA	–	0.1881 (0.0643)	–	–	–	–
var(u_{lkj})	1.0406 (0.2311)	0.1958 (0.0446)	0.5792 (0.1251)	0.2152 (0.0470)	1.9492 (0.4516)	2.6002 (0.5819)
ϕ or var(e_{lkji})	3.6092 (0.0992)	4.6272 (0.1271)	5.0780 (0.1395)	3.9156 (0.1076)	7.6813 (0.2313)	7.7045 (0.2242)

Note: the predicted variables are the number of natural pines (n_4), natural spruces (n_5), seed-origin birches (n_6) and other broadleaves (n_7) on 20 m^2 plots (eq. 1), and the height (cm) of spruces (h_1) and dominant height (cm) of broadleaves (h_2) (eq. 2).
For class variables (i.e. unit not given), if the value is true, 1; otherwise, 0.
OMaT = *Oxalis–Maianthemum* type; OMT = *Oxalis–Myrtillus* type; MT = *Myrtillus* type; VT = *Vaccinium* type; CT = *Calluna* type.

Table 6. Correlations among the stand-level random effects (upper triangle) and plot-level random errors (lower triangle) of the regeneration models for spruce planting, direct seeding and natural regeneration

	n_1	n_2	n_3	n_4	n_5	n_6	n_7	h_1	h_2
Planting									
n_1	1	**-0.30**	-0.14	0.12	**0.73**	-0.08	**0.16**	0.04	0.07
n_2	**-0.13**	1	**0.26**	**0.51**	-0.10	0.01	0.03	**-0.16**	-0.05
n_3	**-0.18**	**-0.05**	1	0.00	0.16	0.11	-0.16	-0.06	**0.23**
n_4	**0.09**	**0.26**	**0.05**	1	**0.20**	0.10	0.09	-0.07	0.05
n_5	**0.56**	**-0.03**	**0.22**	**0.19**	1	0.01	**0.27**	0.04	0.15
n_6	**0.08**	**0.08**	**0.05**	**0.11**	**0.15**	1	**-0.30**	-0.00	0.02
n_7	**0.03**	0.00	**0.09**	**0.02**	**0.08**	**-0.01**	1	0.15	**0.20**
h_1	**0.12**	**-0.03**	0.00	**0.02**	**0.09**	0.00	**0.04**	1	**0.47**
h_2	**-0.04**	**-0.01**	**0.10**	**-0.03**	0.01	**-0.05**	**0.26**	**0.16**	1
Direct seeding									
n_4	--	--	--	1	0.07	-0.07	-0.09	-0.34	**-0.48**
n_5	--	--	--	**0.21**	1	0.07	0.03	-0.21	-0.07
n_6	--	--	--	**0.20**	**0.22**	1	**-0.35**	-0.09	-0.04
n_7	--	--	--	**-0.05**	**0.07**	0.03	1	-0.25	0.18
h_1	--	--	--	0.03	0.04	-0.03	0.02	1	**0.43**
h_2	--	--	--	**-0.13**	0.01	0.02	**0.32**	**0.21**	1
Natural regeneration									
n_4	--	--	--	1	0.07	0.20	0.22	**-0.40**	-0.22
n_5	--	--	--	**0.17**	1	0.27	0.25	-0.10	-0.09
n_6	--	--	--	**0.13**	**0.16**	1	0.11	-0.30	-0.05
n_7	--	--	--	**0.06**	**0.11**	**0.09**	1	0.12	**0.36**
h_1	--	--	--	**-0.07**	**0.04**	**-0.12**	**-0.05**	1	**0.63**
h_2	--	--	--	**-0.06**	**0.11**	0.02	**0.17**	**0.24**	1

Note: the predicted variables are the number of planted spruces (n_1), natural crop-tree pines (n_2) and spruces (n_3), natural pines (n_4), seeded and/or natural spruces (n_5), seed-origin birches (n_6) and other broadleaves (n_7) on 20 m^2 plots (eq. 1), and the height (cm) of spruces (h_1) and dominant height (cm) of broadleaves (h_2) (eq. 2).
Statistically significant correlations are in bold ($p < 0.05$)

one seedling per plot. Considering the height models, the lowest RMSE (19 cm) was found for the height of planted spruces and the highest RMSE (83 cm) for the dominant height of broadleaves on naturally regenerated areas.

Simulation results

Stochastic simulations were conducted to calculate probabilities of obtaining at least a given number of trees per hectare in planting, direct seeding and natural regeneration for spruce. When both planted spruces and natural crop-tree conifers were counted, planting was more effective than direct seeding and natural regeneration (Figure 1). On a disc-trenched and planted site, the simulated probabilities of good and moderate regeneration result were 58% and 97%, respectively. On mounded areas, the corresponding probabilities were 73% and 99%, respectively. However, if only planted spruces were counted, the regeneration results were poorer: the probabilities of good and moderate result on a disc-trenched site were 21% and 76%, and on a mounded site 36% and 87%, respectively.

Table 7. Error statistics (eq. 3) of the submodels for the number of planted spruces (n_1), natural crop-tree pines (n_2) and spruces (n_3), natural pines (n_4), seeded and/or natural spruces (n_5), seed-origin birches (n_6) and other broadleaves (n_7) on 20 m^2 plots, and the height (cm) of spruces (h_1) and dominant height (cm) of broadleaves (h_2)

	Modelling data set			Validation data set		
	E	$\lvert E\rvert$	E^2	E	$\lvert E\rvert$	E^2
Planting						
n_1	-0.0236*	0.8265	1.0873	-0.0563*	0.8504	1.1419
n_2	-0.0034*	0.1909	0.0979	0.0187*	0.2101	0.1177
n_3	0.0146*	0.2447	0.1357	0.0141*	0.2583	0.1617
n_4	0.0194*	0.5569	1.0417	0.0164*	0.5706	1.0931
n_5	0.0224*	0.7115	1.1717	-0.1818*	0.6204	0.7274
n_6	-0.0072^{ns}	0.9712	1.4063	-0.1133*	0.9005	1.1934
n_7	0.0172*	0.9179	1.2432	-0.1324*	0.8646	1.0835
h_1	0.07^{ns}	13.72	351.49	-1.26*	14.70	435.56
h_2	1.15*	37.85	2779.50	-2.65*	42.09	3551.65
Direct seeding						
n_4	0.0565*	0.7294	1.1231	0.1838*	0.7955	1.3242
n_5	-0.0061^{ns}	0.8654	1.2825	-0.5976*	0.8155	0.9010
n_6	-0.0216^{ns}	1.0214	1.3300	-0.6833*	0.9076	1.0838
n_7	0.0417^{ns}	0.9254	1.2161	0.4896*	0.9592	1.3873
h_1	-2.36*	17.41	903.54	8.46*	17.56	782.57
h_2	-1.24^{ns}	38.67	2665.82	-28.17*	39.31	2307.44
Natural regeneration						
n_4	-0.0459*	0.7203	1.2960	-0.2570*	0.6567	0.6751
n_5	-0.0424*	0.8564	1.1744	-0.0294^{ns}	1.1115	1.7707
n_6	-0.0357^{ns}	0.8782	1.3832	-0.0878^{ns}	0.8615	1.2185
n_7	0.0237^{ns}	0.9763	1.3994	0.0784^{ns}	1.0315	1.5868
h_1	-0.65^{ns}	40.00	3640.87	-1.70^{ns}	34.19	1693.89
h_2	-1.09^{ns}	59.73	6952.47	-24.92*	60.65	5215.73

Note: * significant at the 0.05 level; ^{ns} non-significant at the 0.05 level.

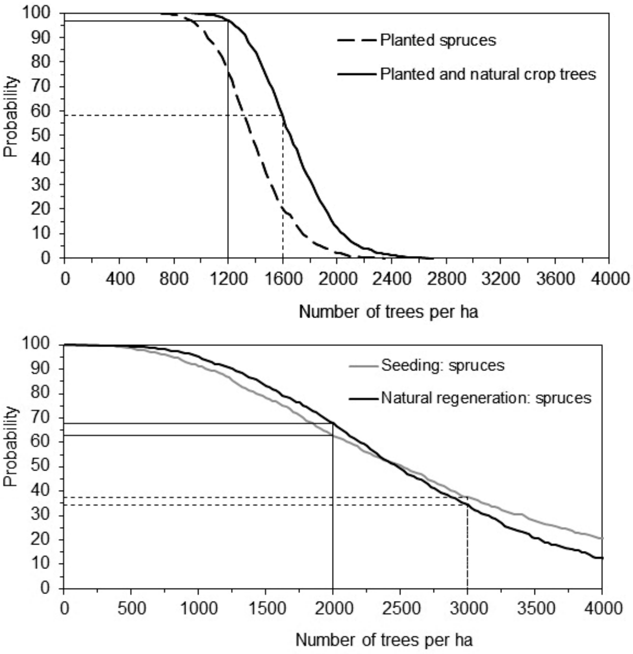

Figure 1. Simulated probabilities of obtaining a given number of trees per hectare in planting (above), direct seeding and natural regeneration (below) for Norway spruce on a disc-trenched site of medium fertility (MT). Dashed and solid lines represent, respectively, the probability of good and moderate regeneration result

Direct seeding and natural regeneration were almost equally effective. The probabilities of a good and moderate regeneration result in direct seeding were 38% and 63% and in natural regeneration 34% and 68%, respectively. The risk of failed or poor regeneration in planting was 3% (on mounded areas 1%), in direct seeding 37% and in natural regeneration 32% (Figure 2).

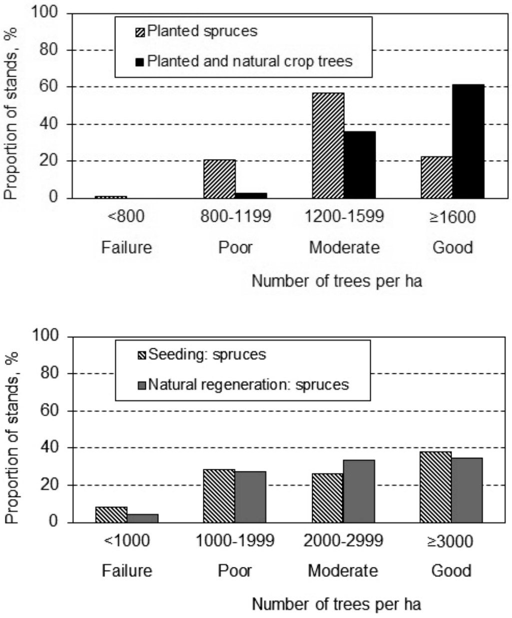

Figure 2. Distribution of regeneration result of the simulated stands. The establishment of seedlings was stochastically simulated for spruce planting (above), direct seeding and natural regeneration (below) on a disc-trenched site of medium fertility (MT)

The plot-level regeneration results illustrate the heterogeneity of establishment of seedlings within a stand (Figure 3). On 70% (on mounded areas 75%) of the plots in a planted stand, the number of crop trees was at least 1500 seedlings ha^{-1}. Correspondingly, on about 45% of the plots in direct-seeded and naturally regenerated stands, the number of seeded and natural spruces was at least 2,500 seedlings ha^{-1}. The proportion of the plots failed to regenerate in planting was 1%, and in direct seeding and natural regeneration about 15%.

If all the simulated stands were cleaned without considering the need for cleaning, the cleaning costs in direct-seeded and naturally regenerated stands were, respectively, 21% and 15% higher than in planted stands (Table 8). In planting, the proportion of the plots needing cleaning was 56%, and accordingly in direct seeding 85% and in natural regeneration 69%. When considering only those simulated stands in which at least half of the plots required cleaning, 40% of planted stands, 99% of direct-seeded stands and 89% of naturally regenerated stands were deemed to require treatment. Consequently, the total cleaning costs in direct-seeded and naturally regenerated stands were 2–3 times higher than in planted stands. Soil preparation method (disc trenching or mounding) had no remarkable effect on the need for, or the costs of cleaning in planted stands.

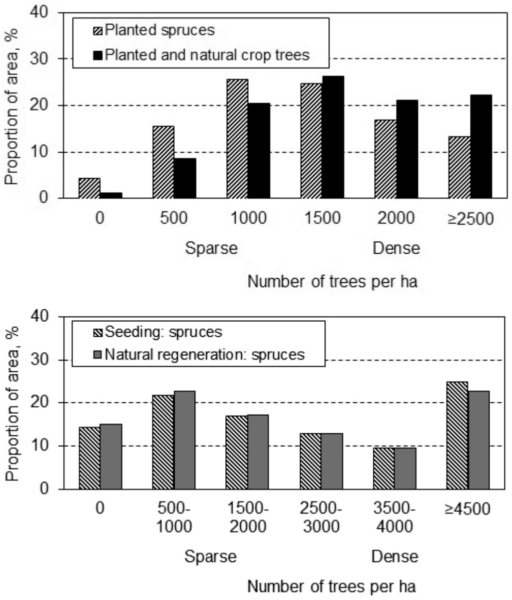

Figure 3. Distribution of the number of seedlings on the plots of the simulated stands. The establishment of seedlings was stochastically simulated for spruce planting (above), direct seeding and natural regeneration (below) on a disc-trenched site of medium fertility (MT)

Table 8. The need for and relative costs of cleaning. The mean costs in planted stands were set to 100. The establishment of seedlings was stochastically simulated for spruce planting, direct seeding and natural regeneration (1,000 stands, 20 plots per stand)

	Planting	Direct seeding	Natural regeneration
Cleaning of all stands			
Mean ± SD relative costs, %	100 ± 12	121 ± 25	115 ± 37
Cleaning of stands where at least half of the plots needed cleaning			
Number of stands	399	985	890
Mean ± SD relative costs, %	100 ± 11	113 ± 23	111 ± 34
Total relative costs, %	100	278	247

Discussion and conclusions

This study presented models of establishment of regeneration for Norway spruce regeneration areas in southern Finland. The regeneration models for spruce direct seeding and natural regeneration were the first ones which consider also the risk of failure. In forest management systems, the models can be used to initiate stand development after regeneration for spruce, and in silvicultural planning, to compare the regeneration methods in the stochastic way. In Finland, the forest owner can select the regeneration method freely but should consider factors such as site conditions and regeneration capacity. According to Saksa et al. (1999), forest owners favor natural regeneration due to e.g. low costs. However, selection of regeneration method always involves risk because the outcome of regeneration (number of seedlings, tree species and size distribution, cleaning costs, etc.) is never known with certainty. Especially the result of direct seeding for Norway spruce has found to be unsatisfactory (Kolström 1991, Mattila 2001, Kinnunen 2002) and therefore the method is not recommended (Metsätalouden kehittämiskeskus Tapio 2006). Also, the result of natural regeneration for spruce has found to be highly variable (Leinonen et al. 1989, Nilsson et al. 2002, Saksa and Nerg 2008, Granhus and Fløistad 2010). Abundant advance spruce seedlings can also be used for regeneration and the most viable spruces can be identified based on e.g. previous growth (e.g. Metslaid et al. 2005, 2007). The results of this study show also that the risk of failed regeneration in direct seeding and natural regeneration for spruce is higher than in planting.

Due to the features of forest regeneration, unexplained, random variation in the regeneration models was very high. Based on the raw residuals of the models, the proportion of response variation explained by the fixed part was only 1–8%. Therefore, forest regeneration models must be inherently stochastic, and to imitate the total variance in response, residual variance should be taken into account in predictions. For a single regeneration area, the distributions of the outcomes of regeneration methods are simulated and thus the uncertainties of different methods of regeneration are compared, as was done in this study. Earlier, for example, Zhou (1999) simulated the regeneration result obtained by pine planting, but he ignored the natural seedlings that would supplement regenerations if the mortality of planted seedlings is high. In this study, both planted spruces and supplementary natural crop-tree conifers were modelled and counted in simulations. Using the estimated variance-covariance matrix of the stochastic components, it was possible to imitate the observed variation in the number of seedlings and species distribution, and assess the need for, and the costs of cleaning in simulated stands.

The data used in this study were not measured for modelling and comparing different regeneration methods, but rather for providing information on quality management of forest regeneration service processes at the FMA and forestry centre levels (Kankaanhuhta et al. 2010). The potential and shortcomings of the regeneration survey data in modelling have been discussed thoroughly by Miina and Saksa (2006, 2008) and Kankaanhuhta et al. (2009). As a result, there are many stand- and plot-level factors affecting regeneration success not included in as predictors. Regardless of effective soil preparation and planting, for example, there was still high unexplained variation in the result of forest regeneration. Therefore, in simulations it was important to consider also the stochastic unexplained variation to obtain more realistic predictions for decisions involving regeneration treatments (Leskinen et al. 2009). Note also that the comparison of regeneration methods may not be fair due to unbalanced data and missing cells in the experimental design matrix. In this study, the comparison of regeneration methods was based on the minimum threshold density values of planted, direct-seeded and natural seedlings ha^{-1} that have been used earlier in Finland (e.g. Saksa and Kankaanhuhta 2007). However, the quality of regeneration result strongly depends on the minimum threshold density values applied as well as the tree species and types of seedlings counted in.

The models should not be used to predict the regeneration establishment in situations that were rare in the modelling data sets (e.g. spruce planting on poor sites) or that are not feasible in practice (e.g. direct seeding without site preparation). The submodels for the number of natural seedlings in planted and direct-seeded areas should be used with a caution. Part of the regeneration area may have been spared soil preparation and planting/direct seeding due to advance regeneration or high probability of good natural regeneration. In this case, the submodels may overpredict the natural regeneration of seedlings on unprepared areas.

On regeneration areas executed by FMA, the number of planted spruces and the number of natural spruces was slightly higher than on regeneration areas executed by forest owners. This could be explained, for example, by better quality control, planting more seedlings ha^{-1} or selecting sites more suitable for natural regeneration when the regeneration activities were carried out by FMA professionals. Though there were several ecological factors affecting the regeneration result (weather and soil conditions, damages, etc.), it would be possible to improve the quality of regeneration result by selecting the most suitable regeneration chain for a given regeneration area and improving the performance of regeneration work (Kankaanhuhta et al. 2009, 2010).

Miina and Saksa (2006) have fitted a model for the establishment of seedlings in spruce planting using a data set of the same regeneration survey database. Their data set was collected mainly from the Savonia region in eastern Finland during the years 2000–2002 (year 2003 was used in validation). In this study, the regeneration model for spruce planting was fitted using the data set collected during the years 2003–2005 (year 2006 was used in validation). The main difference between the model of this study and the earlier one was in the effect of soil preparation. According to Miina and Saksa (2006), on unprepared plots the number of planted spruces was 21% lower (95% confidence interval -17% – -25%) (in this study 9% lower (-6% – -11%)) than that on disc-trenched or patched plots, and mounding increased the number of planted spruces by 7% (3% – 11%) (in this study by 9% (7% – 10%)). Kankaanhuhta et al. (2010) have used the whole database (years 2000–2006) for modelling the number of planted spruces. According to their model, on unprepared plots the number of planted seedlings was reduced by 20% (-17% – -23%), and mounding increased the number of planted seedlings by 9% (7% – 11%). In the regeneration survey database, mounding proved to yield the best result in planting. In the case of unprepared plots, the reduction in the number of planted spruces seems to depend on the data set of the database.

The estimated models enabled us to compare the between-stand and within-stand variation involved in different methods of regeneration for spruce, as well as the need for, and the costs of cleaning. The results showed that planting was the most effective and guaranteed method for establishing spruce stands. Selecting the economically preferred method of regeneration would require additional simulations of the costs of regeneration, future development and wood quality of trees, etc. (e.g. Pukkala et al. 2010, Tahvonen et al. 2010). The regeneration models could be connected to a stand simulator where they would facilitate the predictions of the establishment of seedlings after regeneration cutting and spruce planting, direct seeding or natural regeneration. After that, simulations covering the whole rotation period and stand-level economic optimization could be used to find the most profitable method of regeneration.

In conclusion, the probability of a good regeneration result can be increased by more careful selection of regeneration and soil preparation method. Planting on mounded areas was the most effective and guaranteed method of regeneration for spruce. Direct seeding and natural regeneration for spruce cannot be recommended due to the high risk of failure.

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ПРОГНОЗ РЕЗУЛЬТАТОВ ЛЕСОВОЗОБНОВЛЕНИЯ НА УЧАСТКАХ ПОСАДОК ЕЛИ ОБЫКНОВЕННОЙ (*PICEA ABIES*) В ЮЖНОЙ ФИНЛЯНДИИ

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Резюме

В рамках исследования прогнозировался результат лесовозобновления ели обыкновенной (*Picea abies* (L.) Karst.) возрастом 3–5 лет на участках, засаженных саженцами, прямым посевом и при естественном лесовозобновлении в Южной Финляндии. Результат лесовозобновления оценивался по количеству высаженных саженцами, прямым посевом и восстановившихся самосевом деревьев, а также по высоте елей и деревьев лиственных пород. Для каждого из способов лесовозобновления составлялась отдельная многоуровневая модель с несколькими переменными. Модели приводились в соответствие с материалами, собранными на участках лесовозобновления. Для описания моделей использовались индексы, характеризующие место, почву и подготовку почвы. При помощи стохастического моделирования сравнивались результаты методов возобновления ели и их распределение, а также возможность проведения раннего прореживания.

Вероятность хорошего результата лесовозобновления составила при посадке саженцами 58%, прямым посевом 34% и при естественном лесовозобновлении 38% при подготовке почвы боронованием. На участках с окучиванием хороший результат достигался с вероятностью 73%. Риск неудачи и не удовлетворительный результат лесовозобновления составил при посадке саженцами 3%, при прямом посеве 37% и при естественном лесовосстановлении 32%. Доля модельных посадок, где не менее, чем на половине площади требовалась прочистка, составили при посадке саженцами 40%, прямым посевом 99% при естественном лесовозобновлении 89%. Посадка ели саженцами является наиболее эффективным и приемлемым способом возобновления. Прямой посев и естественное лесовозобновление ели сопровождается высоким риском неудачи.

Ключевые слова: обработка почвы, лесопосадка, посев, уход за саженцами, стохастическое моделирование