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Open geospatial data can predict the early field performance of Scots pine, Norway spruce and silver birch seedlings in Nordic boreal forests

Jari Miina [a], Aura Salmivaara [b], Karri Uotila [c], Jaana Luoranen [c] and Saija Huuskonen [b]

[a]Natural Resources, Natural Resources Institute Finland (Luke), Joensuu, Finland; [b]Natural Resources, Natural Resources Institute Finland (Luke), Helsinki, Finland; [c]Natural Resources, Natural Resources Institute Finland (Luke), Suonenjoki, Finland

ABSTRACT

Accurate knowledge of site conditions and their effects on regeneration establishment is important for selecting the most appropriate tree species and regeneration methods for a given regeneration site. This study examined the response of the first-year field performance of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and silver birch (*Betula pendula* Roth.) seedlings in boreal forests to variables available in open forest and natural resources datasets. Survival, height increment and damage of planted tree seedlings and the success of direct seeding of pine were analysed on a total of 284 plots (1000 m^2) in 18 regeneration experiments established in 2020–2022 in southern and central Finland. The height increment of silver birch was higher than that of conifers, while the lowest mortality rate was found for spruce. In the generalised linear mixed models, topographic wetness index, soil texture, site type and growing stock at clearcut explained the species-specific survival and height increment of planted seedlings and the success of pine seeding. Low-cost, open geospatial data effectively provide useful details on the site conditions suitable for diversifying tree species composition in boreal forests instead of monocultures.

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Introduction

In forest regeneration, information on site and soil conditions is used to support forest managers choose the tree species and regeneration and site preparation methods. However, the assessment of site and soil conditions needs to be operational and cost efficient. Therefore, the suitability of open geospatial data for producing effective and low-cost measures of site and soil properties should be tested. As an earlier example, the topographic wetness index (TWI) and the depth-to-water index (DTW) have been used to produce trafficability maps for mechanised logging operations to reduce environmental impacts (Hoffmann et al. 2022). Similarly, digital elevation model (DEM) derived variables such as surface curvature, slope position and TWI together with soil texture have been used to model forest soil moisture to identify drought – and waterlogged-prone areas (Akumu et al. 2019). However, the use of open geospatial data does not always provide a sufficient level of information, as Launiainen et al. (2022) found that water retention characteristics (WRC) could not be predicted with any combination of open geospatial data. They suggested parameterising WRC as a function of fertility type, which is also openly available, to estimate hydraulic properties for sites without specific soil data. In this study, we analysed the potential of open geospatial data to explain the early performance of tree seedlings, and thus to support the planning of forest regeneration activities.

In recent decades, the majority of seedlings planted/used in Nordic countries have been conifers. In 2021, 67%, 44% and 96% of the seedlings planted in Finland, Sweden and Norway, respectively, were Norway spruce (*Picea abies* (L.) Karst.), and 29%, 52% and 4% were Scots pine (*Pinus sylvestris* L.) (Solvin et al. 2023). Due to increased spruce planting in the 2000s, a quarter of the spruce-dominated stands in Finland are less than 20 years old (Korhonen et al. 2021). Currently, spruce planting is a prevailing practice on nutrient-rich sites that are also suitable for silver birch (*Betula pendula* Roth.). Spruce is also planted on nutrient-poor and coarse-textured sites where pine stands are found more suitable than spruce stands (Levula et al. 2003). The main reason for the dominance of spruce seedlings in regeneration is the high risk of browsing damage by moose (*Alces alces*) to young pine and broadleaves stands (Nevalainen et al. 2016). There is a practical need both to diversify the use of silver birch and pine and to establish mixed forests instead of regenerating of pure spruce stands. To this end, the field performance of pine, spruce and silver birch regenerated with the current materials and methods in different site conditions should be evaluated. Such knowledge could be used to select more precisely the tree species and regeneration methods that are appropriate for the specific site conditions. With the principles of precision forestry (Venanzi et al. 2023), accurate data and advanced knowledge allow for site-specific management decisions.

CONTACT Jari Miina jari.miina@luke.fi Natural Resources Institute Finland, Yliopistokatu 6B, 80100 Joensuu, Finland

Mechanical site preparation is carried out during the regeneration phase. In 2021, mounding was used on 74% of mechanically prepared sites in Finland, disc trenching on 15% and patch scarification on 9% of sites (Peltola and Vaahtera 2022). The three main methods of mounding used are spot mounding, soil inversion, and ditching and mounding. In spot mounding, an elevated planting place is created by turning the soil on top of the unprepared soil, so that the mound contains a double humus layer under the mineral soil, and next to the mound is a patch from which the soil is taken (Sikström et al. 2020). In soil inversion, the soil is turned in the same place from which it was dug, so that a single layer of humus is under the mineral soil layer. On wet soils, elevated planting spots are also created by digging ditches and dropping soil onto the unprepared soil. In disc trenching, a continuously advancing device creates furrows covered with mineral soil by turning the humus layer next to the furrows, and in patch scarification the humus layer is removed from a small area to create patches covered with mineral soil. Because of competing vegetation, for example, intensive site preparation methods are needed on nutrient-rich sites and in moisture soil conditions to create a sufficient number of planting and sowing spots favourable to seedling survival and growth. In Finland, patch scarification and disc trenching are used on nutrient-poor and coarse-textured sites suitable for pine. Patching is also used on very stony sites, both nutrient-rich and poor, when other methods are difficult to use properly. Mounding is usually used on nutrient-rich sites. Mainly spruce and broadleaves, but usually also pine, are planted in mounds.

Site preparation increases the survival and growth of silver birch, pine and spruce (Raulo and Rikala 1981; Heiskanen et al. 2013; Nilsson et al. 2019; Sikström et al. 2020; Nordin et al. 2023). The best field performance results are obtained by planting seedlings in mounds (Raulo and Rikala 1981; Saksa 2011) and in inversion (Sikström et al. 2020), and by mechanical direct seeding of pine in combination with site preparation (Kankaanhuhta et al. 2009). In planting, one of the most important effects of site preparation is its protection against pine weevil (*Hylobius abietis*) feeding (Örlander and Nilsson 1999; Petersson and Örlander 2003; Petersson et al. 2005; Luoranen et al. 2017, 2022a; Wallertz et al. 2018). Growth-enhancing effects of site preparation, especially in elevated planting spots and those with organic material under the mineral soil cover (e.g. mounds, inversions) are observed even 10 years after spruce planting (Uotila et al. 2022). This also increases the carbon stocks 25 years after planting on prepared sites (Mjöfors et al. 2017). Therefore, site preparation methods that do not reduce the amount of organic material in planting spots (e.g. mounding, inversion) should be preferred for spruce (Nilsson et al. 2019; Uotila et al. 2022) and silver birch (Raulo and Rikala 1981).

Climate change increases the risk of damage in forests, especially in spruce stands. Based on climate change scenarios, drought periods in spring and early summer are predicted to become more frequent in the northern boreal climate zone (Ruosteenoja et al. 2018). Among commercially important tree species, spruce is the most sensitive to drought and wet soil conditions (Jansons et al. 2016), and its performance may suffer in Finland's future warming climate (Kellomäki et al. 2018). Deep planting in mounds has been found to reduce the risk of drought damage to spruce (Luoranen and Viiri 2016). A warming climate also increases the risk of outbreaks of the spruce bark beetle (*Ips typographus*) outbreaks in spruce stands and the wood decay due to *Heterobasidion* root rot in coniferous forests, which threatens spruce in older stands (Venäläinen et al. 2020). Stressful conditions, such as summer droughts, further increase the risk of bark beetle damage. Climate models also predict that snowfall may decrease in most parts of northern Europe (Räisänen 2016), exposing newly planted seedlings to fluctuating winter weather conditions during snowless winters (Sutinen et al. 2008). These changing weather conditions in the boreal zone also challenge the forest regeneration, increasing the risk of damage to newly planted seedlings (Luoranen et al. 2018, 2022b, 2023). There may also be differences between tree species in their responses to climate change. For example, winter damage (e.g. frost heaving, drought, damage caused by a hard winter or winter desiccation) was more common in newly planted pine seedlings than in spruce seedlings (Luoranen et al. 2018). Tree species composition can also influence pine weevil feeding, and in mixed forests pine seedlings are more likely to be attacked than spruce seedlings (Wallertz et al. 2005).

Soil texture type and site fertility influence the risk of damage to planted seedlings and seedling emergence in direct seeding. For example, the risk of abiotic damage (drought, winter damage) to planted spruce seedlings has been observed to increase on coarse-textured, nutrient-poor site types and on the other hand on fine-textured, nutrient-rich site types (Luoranen et al. 2018, 2022b, 2023). On fine-textured soils, the risk of frost heaving increases for both direct seeding (de Chantal et al. 2003, 2006) and planting (Örlander et al. 1991; Luoranen et al. 2011, 2022b). Furthermore, regeneration outcomes have been found to be impaired when direct seeding of pine is used in nutrient-rich, fine-textured soils or on wet sites (Kankaanhuhta et al. 2009). This highlights the importance of identifying site conditions and selecting the tree species and regeneration methods that will provide the best possible regeneration outcomes.

Johansson et al. (2015) have studied the early performance of planted spruce and pine seedlings in field experiments established in northern Sweden. They found that a larger seedling container size increased the height growth of pine, but no differences were found for spruce. In addition, despite higher growth, pine seedlings were more susceptible to damage for a longer period after establishment than spruce seedlings. In southern Sweden, Nordin et al. (2023) have studied the growth and mortality of pine, spruce and silver birch seedlings planted in different planting positions in the mounds under varying soil moisture conditions. According to their results, under wet conditions, the survival rate and growth of conifers increased in higher positions in the mounds, whereas silver birch was less dependent on a specific planting position.

More comparable information is needed on the field performance of the main tree species, namely pine, spruce and silver birch, under different site conditions in boreal forests. Such information is particularly important when establishing mixed forests through a combination of planting, sowing and natural regeneration. Currently, forest stands are mainly established as monocultures by sowing or planting a single tree species on a given site. The transition to mixed forests requires a comprehensive understanding of the factors that influence the survival and growth of each tree species. This knowledge is essential for identifying sites suitable for different tree species and for establishing mixed forests.

The study aimed to compare the first-year field performance of Scots pine, Norway spruce and silver birch seedlings regenerated in different site and soil conditions in southern and central Finland, and to analyse the potential of open geospatial data to explain the early performance of seedlings. The field performance of the planted seedlings was compared by analysing their survival, height increment and damage after the first growing season. The success of seedling emergence in direct seeding of pine was also analysed. The data consisted of 18 regeneration experiments established by Natural Resources Institute Finland in 2020–2022. The early performance of seedlings was analysed using open-source variables such as static wetness indices, monthly climatic factors, and site and stand characteristics at the time of clearcutting as potential predictors in generalised linear mixed-effects models. The additional potential of field-assessed soil texture and soil carbon/nitrogen ratios to explain seedling performance in the field was also determined.

Material and methods

Study areas

The study material consisted of the permanent regeneration experiments (SEKAVA) established during 2020–2022 (Table 1). The experiments were located in 18 stands in southern and central Finland, ranging from 60° 38′ N to 62° 55′ N latitude and 24° 14′ E to 31° 03′ E longitude (Figure 1). The site conditions included fine, medium and coarse textured mineral soils, and the following site types: rich – *Oxalis-Myrtillus* type (OMT, herb-rich), medium – *Myrtillus* type (MT, mesic) and rather poor – *Vaccinium* type (VT, sub-xeric) (Cajander 1949; Tonteri et al. 1990). The long-term average effective temperature sum (period 1980–2010, the sum of degree days above 5°C, d.d.) varied between 1123 and 1394 d.d. The regeneration areas were clearcut mainly during the winter season. Harvesting residues were collected from 10 stands and left in 8 stands. Retention trees were not left in the experimental plots to avoid shading and resource competition from them.

Experimental design

The experimental design was aimed at finding the most appropriate combinations of tree species and regeneration methods most suitable for different site conditions in the Nordic boreal forest to ensure the establishment of biodiverse, viable and productive mixed forests. The experiments included the following treatment sets: pine−spruce, pine−birch or spruce−birch, depending on the site type (Tables 1 and 2). The treatments included both pure monocultures (pine seeding, pine planting, spruce planting, birch planting) and mixtures (pine seeding and spruce planting, pine and spruce planting, spruce and birch planting, pine and birch planting, spruce planting and naturally regenerated birch, pine planting and naturally regenerated birch). In each stand three replications were established for each treatment, except in two stands (SEKAVA 12 and 15) where only two replications were included due to the smaller size of the regeneration area. In four stands (SEKAVA 3–5 and 16) two different treatment sets were combined. In two stands (SEKAVA 13 and 15), an additional treatment was the planting of somatic embryogenically produced spruce seedlings (SE spruce) as a monoculture. In this study, SE spruces were

Table 1. Description of 18 regeneration experiments of the SEKAVA trial (Forest Management Regimes of Mixed Forests).

SEKAVA	Site type[a]	TS[b]	Clearcutting	Harvesting residues	Site preparation[c]	Regenerated by	Number of plots	Treatment set[d]
1	MT	1181	Apr 2020	Removed	Soil inversion	Jun 24, 2020	15	Pine−spruce
2	MT	1181	Apr 2020	Removed	Soil inversion	Jun 30, 2020	12	Spruce−birch
3	MT	1272	Dec 2020	Removed	Soil inversion	May 31, 2021	24	Pine−birch, pine−spruce
4	MT	1256	Dec 2020	Removed	Soil inversion	Jun 4, 2021	24	Spruce−birch, pine−spruce
5	MT	1256	Dec 2020	Removed	Soil inversion	Jun 11, 2021	24	Spruce−birch, pine−birch
6	OMT	1192	Jan 2021	Removed	Soil inversion	Jun 7, 2021	12	Spruce−birch
7	VT	1210	Jan 2021	Removed	Soil inversion	Jun 18, 2021	15	Pine−spruce
8	VT	1100	Mar 2021	Left	Soil inversion	Jun 30, 2021	15	Pine−spruce
9	VT	1177	Jun 2020	Left	Soil inversion	Jun 2021	15	Pine−spruce
10	VT	1215	Autumn 2020	Left	Soil inversion	Jun 28, 2021	15	Pine−spruce
11	VT	1123	Spring 2019	Left	Soil inversion	Jul 2, 2021	15	Pine−spruce
12	MT	1255	Spring 2020	Left	Spot mounding	Jun 7, 2021	10	Pine−spruce
13	OMT	1291	Mar 2022	Removed	Soil inversion	May 31, 2022	15	Spruce−birch + SE spruce
14	OMT	1269	Jan 2022	Removed	Soil inversion	Jun 2, 2022	12	Spruce−birch
15	OMT	1256	Jan 2022	Left	Soil inversion	Jun 8, 2022	10	Spruce−birch + SE spruce
16	MT	1279	Feb 2022	Left	Soil inversion	Jun 16, 2022	24	Spruce−birch, pine−birch
17	MT	1254	Apr 2022	Left	Soil inversion	Jun 8, 2022	15	Pine−birch
18	OMT	1394	Feb 2022	Removed	Soil inversion	May 2022	12	Spruce−birch

[a]OMT = rich – *Oxalis–Myrtillus* type; MT = medium – *Myrtillus* type; VT = rather poor – *Vaccinium* type.
[b]Mean effective temperature sum (5̊C threshold) in degree days during the period of 1980–2010.
[c]Patch scarification was used for direct seeding of pine on VT site type.
[d]Tree species used in planting; direct seeding of pine was also used in the pine−spruce treatment. SE spruce = spruce seedlings produced via somatic embryogenesis.

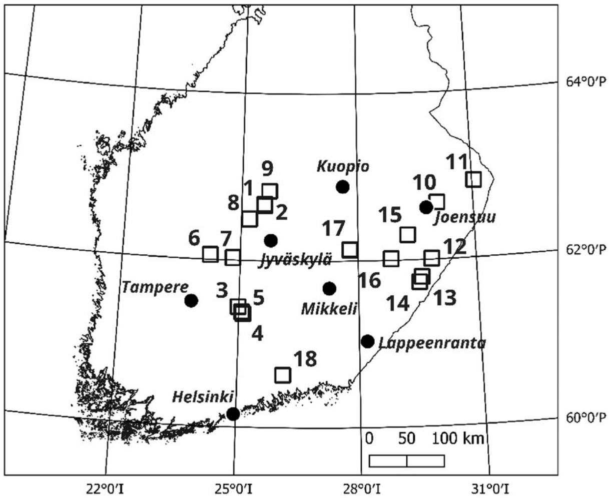

Figure 1. Location of 18 regeneration experiments of the SEKAVA trial in southern and central Finland.

Table 2. Regeneration methods and tree species (target density ha^{-1} in parentheses) used in the treatment sets of spruce–birch, pine–birch and pine–spruce, and site types on which each treatment set was applied (OMT, MT, and VT = rich, medium, and rather poor sites, respectively). Spruce seedlings produced via somatic embryogenesis (SE spruce) were planted on two OMT sites.

Spruce–birch on OMT and MT sites	Pine–birch on MT site	Pine–spruce on MT and VT sites
Spruce planting (1800)	Pine planting (2200)	Pine planting (2200)
Silver birch planting (1600)	Silver birch planting (1600)	Spruce planting (1800)
Spruce (900) and silver birch (900) planting	Pine (1000) and silver birch (1000) planting	Pine (1100) and spruce (1100) planting
Spruce planting (900) and natural birch (900)	Pine planting (1000) and natural birch (1000)	Spruce planting (1100) and pine seeding (1100)
SE spruce planting (1800)	Pine seeding (2200)	Pine seeding (2200)

included in the spruce seedlings. The total number of treatment plots was 284, varying from 10 to 24 plots per stand depending on the treatment set and the number of replications.

The size of the treatment plots was 1000 m^2 surrounded by a 5 m buffer zone (4 m buffer zone in SEKAVA 1 and 2) where the same treatment was applied. Planting densities for pure silver birch, spruce and pine were 1600, 1800 and 2200 seedlings per hectare, respectively, and 2200 spots per hectare were direct seeded for pine (Table 2). The 50/50 mixtures with tree-wise mixing patterns were established by planting a total of 1800, 2000 and 2200 seedlings per hectare in spruce–birch, pine–birch and pine–spruce mixtures, respectively. The 50/50 mixtures were also established by planting spruce (1100 seedlings ha^{-1}) and sowing pine (1100 spots ha^{-1}). In addition to these artificially regenerated mixtures, the pine–natural birch and spruce–natural birch plots were established by planting only half of the target density, i.e. 1000 pine seedlings ha^{-1} and 900 spruce seedlings ha^{-1}, in order to allow the same number of birches (silver and downy (*Betula pubescens* Ehrh)) to regenerate naturally, mainly on disturbed soils (Lehtosalo et al. 2010), and to complement the conifers. No birch seed trees were present in the experimental areas; seed dispersal from adjacent stands was expected.

The target density of site preparation was guided based on the regeneration density of the plot. On OMT and MT sites, site preparation was soil inversion, except one MT site, where spot mounding was used (Table 1). Similarly, on VT sites, planting spots were prepared by soil inversion, but sowing spots were prepared by patch scarification. Therefore, in the mixed treatment of pine seeding and spruce planting, every second regeneration spot was prepared by soil inversion and every second by patch scarification.

Regeneration was caried out in the first growing season after clearcutting, except in SEKAVA 9 and 12 where the time difference between clearcutting and regeneration was one growing season, and in SEKAVA 11 where it was two growing seasons. Site preparation was done in the same spring with planting and direct seeding, except in SEKAVA 12, where spot mounding was done in the previous autumn. The aim of site preparation was to create mounds with a radius of about 60 cm and patches covered with mineral soil to prevent pine weevil damage. The timing of regeneration during the growing season varied between the experiments, ranging from 27 May (SEKAVA 3) to 2 July (SEKAVA 11). Seedlings were planted 5 cm deep in the centre of the mounds using the planting tubes, but at least half of the stem had to be above ground. Approximately 10–15 pine seeds were sown in the centre of the mounds or patches (i.e. 130–200 g per hectare with a weight of 6 g for 1000 seeds and 2200 sowing spots ha^{-1}).

Depending on the landowners' practices, seedlings stored in the freezer and packed in cardboard boxes or seedlings overwintered outdoors and delivered to the forest in open trays were used for planting. All seedlings were grown in medium sized, hard walled plastic containers. The exact container type was not known in all cases, but in known cases it was Plantek PL81F (plug volume 85 cm^3, growing density 546 seedlings m^{-2}, BCC Ab, Landskrona, Sweden). Conifer seedlings were one year old, grown according to the Finnish guidelines for pine and spruce container seedlings (Lilja et al. 2010) and treated against pine weevil (Karate® Zeon, lambda-cyhalothrin) before packing and delivery. Silver birch seedlings (mean/minimum height 20/15 cm, 23/14 cm, or 47/28 cm) were sown in June and grown for only a few months in the nurseries and planted the following spring after overwintering (Pikkarainen et al. 2021). For regeneration, genetically improved material suitable for the prevailing climatic conditions was used, and the same seed material (germination capacity in 21 days 86–99%) was used for sowing pine as for growing pine seedlings in the Finnish nurseries.

The experiments were established by Natural Resources Institute Finland together with the landowners (Finsilva Oyj, Tornator Oyj, UPM Kymmene Oyj Forest and Metsähallitus Metsätalous Oy) and their subcontractors. As, for example, several contractors and nurseries supplied the regeneration material, it was not possible to control for all the factors (e.g. quality of site preparation, seedling transport, handling and planting) that might affect the regeneration outcome in the experiments.

Tree measurements

After the first growing season (August to October), the location, total height (cm) and height increment of the current year (cm) were measured for each planted seedling on the 1000 m^2 rectangular plots. The height increment of conifers was measured based on branch whorls. In autumn 2020, silver birch seedlings (SEKAVA 2) were not measured by height increment, but only by the total tree height. Later, the height increment of silver birch was also measured based on terminal bud scars. In direct seeding, the location of sowing spots and the number of pine seedlings in the sowing spot (patch or mound) were determined on the 1000 m^2 plot. In addition, the locations of empty planting and sowing spots were recorded. The symptoms, agents and degree of damage to the planted seedlings were also recorded. The degree (severity) of damage was determined from a silvicultural point of view as follows: healthy; recovery, i.e. minor damage from which the seedling will recover or has recovered; damage, i.e. moderate damage that will reduce the amount or quality of wood; and dead, i.e. severe damage that will kill or has killed the seedling.

Soil sampling

Soil samples were taken in the spring or autumn of the regeneration year. On each 1000 m^2 plot, twenty soil cores of the organic layer (fibric and humic organic matter, excluding the litter layer) and ten soil cores of the mineral layer were taken from two depths, 0–10 cm and 10–20 cm, separately with a steel auger (diameter 58 mm). The thickness of the organic layers and mineral layers was measured. The samples were combined in plastic bags to form one composite organic layer sample and two composite mineral soil samples per depth. The composite samples were placed in the open bags at room temperature, taken shortly to the laboratory and stored at 2–3 °C for a short time or at −18 °C for a long time prior to analysis. The texture of the mineral soil samples was defined by visual inspection and feel test

Table 3. Descriptive statistics of the field-assessed and open-source variables of the 1000 m^2 plots ($N = 284$) of 18 regeneration experiments (the SEKAVA trial) in southern and central Finland.

Continuous variable[a]	Mean	SD	Range
C:N ratio			
Organic soil layer	32.2	8.2	18.8–51.5
Mineral soil layer of 0–10 cm	24.2	6.3	11.2–44.2
Mineral soil layer of 10–20 cm	18.7	6.4	3.3–34.6
Digital elevation model, m	129.3	38.4	32.2–207.8
Topographic wetness index (TWI in thousands)	7.3	1.0	5.2–9.9
Depth to water index with 0.5 ha threshold, m	1.0	0.8	0.0–4.0
Depth to water index with 1 ha threshold, m	1.8	1.6	0.0–7.9
Depth to water index with 4 ha threshold, m	3.3	2.5	0.1–10.2
Depth to water index with 10 ha threshold, m	4.9	3.4	0.2–14.2
Topographic positional index, m	0.001	0.004	−0.010–0.023
Terrain ruggedness index, m	0.34	0.17	0.11–1.07
Slope, degree	3.6	2.1	0.9–12.2
Aspect, degree	152.3	60.7	24.9–297.7
Erosion risk, ton ha^{-1} $year^{-1}$	4.8	4.8	0.7–32.3
Forest trafficability index[b]	1.8	1.0	1.0–6.0
Mean temperature in June, °C	17.7	1.2	15.6–18.9
Mean temperature in July, °C	18.8	1.5	14.9–20.3
Precipitation sum in June, mm	53.9	11.6	30.8–75.2
Precipitation sum in July, mm	59.4	22.4	29.4–107.8
Potential evaporation in June, mm	157.4	13.0	133.3–180.1
Potential evaporation in July, mm	149.4	19.8	107.8–170.9
Growing stock at clearcut			
Total volume, m^3 ha^{-1}	282.9	99.0	153.6–636.7
Proportion of pine in volume, %	40.4	34.8	0.0–98.1
Proportion of spruce in volume, %	50.8	33.3	0.0–99.8
Proportion of broadleaves in volume, %	8.8	11.1	0.0–73.7

Categorical variables	Field assessment[c]		Open-source data[d]	
	N	%	*N*	%
Site type				
Rich (*Oxalis-Myrtillus* type)	61	21.5	81	28.5
Medium (*Myrtillus* type)	148	52.1	144	50.7
Rather poor (*Vaccinium* type)	75	26.4	59	20.8
Soil texture				
Fine	34/34	12.0/12.0	62/14	21.8/4.9
Medium	34/53	12.0/18.7	129/184	45.4/64.8
Coarse	216/197	76.1/69.4	93/86	32.7/30.3

[a]Continuous variables were obtained from open-source databases, except for C:N ratios, which were measured from soil samples.
[b]Forest trafficability index describes the carrying capacity of the soil (the higher, the lower): 1 – in any season; 2 – in summer, mineral soils; 3 – in summer during the dry season, mineral soils; 4 – in summer, peatlands; 5 – in summer during the dry season, peatlands; and 6 – only during frost or a thick layer of snow.
[c]Site type was assessed at the experiment level, and soil texture of two mineral soil layers (0–10 cm/10–20 cm) was assessed at the plot level.
[d]Site type was obtained from the database of the Finnish Forest Centre, and soil texture class was obtained from two open-source databases (the Finnish Forest Centre/the Geological Survey of Finland).

based on the major fraction of coarse (>0.2 mm, particle size is observable), medium (0.02–0.2, individual particles are distinguishable) and fine (<0.02, individual particles are not visible) particles (Table 3). Total carbon (C) and nitrogen (N) concentrations were measured from air-dried samples by the Dumas method using a Leco elemental analyser (Leco Corporation, USA). C:N ratios were calculated separately for the organic and mineral layers.

Open-source data

Several topographic, forest, climatic and geological variables available from open data sources were used to analyse the field performance of planted seedlings and the success of direct seeding (Table 3). First, the open-source variables were determined for each planted, sown and empty spot located on the 1000 m^2 plots. The plot-level values were then calculated as the mean of the spot-level variables.

The terrain-derived variables topographic wetness index at 16 m resolution (TWI in thousands; the higher, the wetter) and depth-to-water index with different thresholds at 2 and 16 m resolution (DTW; the higher, the drier) were obtained from Salmivaara (2016) and Salmivaara (2020), respectively. Elevation, slope, aspect, topographic position index (TPI; elevation difference between a central grid cell and the mean of its surrounding cells) and terrain ruggedness index (TRI; root mean square deviation of elevation differences between a central grid cell and its surrounding cells) variables were calculated from the digital elevation model (National Land Survey of Finland 2023) at 2 and 16 m resolution.

Site and stand characteristics (e.g. site type, soil texture and tree species-specific volumes) at the time of clearcutting were obtained from the Finnish Forest Centre's forest resources databases or from landowners. The Finnish Forest Centre's open access data cover 95% of the privately owned forests in Finland. Growing stock variables of pine, spruce and broadleaves at 16 m resolution were based on aerial laser scanning (ALS), photography and field assessment (Finnish Forest Centre 2022a). In the forest resources data, information on site type and soil texture came from two sources: forest use declarations for cuttings submitted to the Finnish Forest Centre (149 out of a total of 284 plots) or the multi-source national forest inventory (MS-NFI) data (135 plots) produced by Luke (Mäkisara et al. 2019; https://kartta.luke.fi/opendata/valinta-en.html). Site variables reported in the forest use declaration were assessed visually in the field, while in the MS-NFI, site variables are estimated using field data, satellite imagery, digital map data and other georeferenced data.

Besides the forest resources databases, information on soil texture can also be obtained from the databases of the Geological Survey of Finland (2022). The superficial deposits at scales of 1:20,000, 1:50,000 or 1:200,000 were downloaded and classified into peat and fine, medium and coarse mineral soils corresponding to the soil sample classification.

Climatic variables such as monthly mean temperatures, precipitation sums and potential evaporation during the growing season (May-August) were extracted from the closest grid (1 × 1 km) in the gridded datasets of the Finnish Meteorological Institute (2022). The erosion risk index was used to describe the susceptibility of the surface soil to water erosion at a resolution of 2 m (Räsänen 2021). The forest static trafficability index developed by Arbonaut Ltd. was obtained from the Finnish Forest Centre datasets (2022b). The forest static trafficability index at 16 m resolution is a combination of topographic wetness information, stand volume and soil type. The index describes the carrying capacity of the forest floor, i.e. the season when mechanised harvesting is possible.

Data analyses

The first-year field performance of spruce, pine and silver birch was compared at the 1000 m^2-plot level. The plot-level responses of the species-specific survival and height increment of planted seedlings as well as the success of direct seeding of pine to both field-assessed and open-source variables were analysed using generalised linear mixed models (GLMM). First, GLMMs were fitted using only open-source variables as potential predictors and including statistically significant ($p < 0.05$) predictors in the models. The aim was to analyse the potential of open geospatial data to explain seedling field performance. Secondly, field-assessed variables (C:N ratio and soil texture) were also used as predictors in the GLMMs fitted in the first stage. Only statistically significant ($p < 0.05$) field-assessed or open-source variables were included in the re-fitted GLMMs. The additional potential of field-assessed variables to explain seedling field performance was determined by comparing the coefficients of determination (R^2) of the GLMMs fitted without and with field-assessed variables. Pseudo-R^2 values were calculated using the function r.squaredGLMM in the R package MuMIn (Bartoń 2020) and only fixed predictors (i.e. marginal models).

The survival of planted seedlings and the success of direct seeding were modelled using a multi-level binomial model with a logit-link function, and the height increment of planted undamaged seedlings was modelled using a multi-level quasi-Poisson model with a log-link function (McCulloch and Searle 2001). As damage had reduced the height increment of seedlings, the height increment model was only fitted for healthy seedlings. Due to the hierarchical and unbalanced data structure, the random, normally distributed between-experiment and between-plot effects were included in the intercepts of the models. In the survival and height increment models, the plot-level random effect was included because two species-specific observations were obtained from the plots of the 50/50 mixtures.

The function glmmPQL in the R package MASS (Venables and Ripley 2002) was used for model fitting, and the R package effects (Fox 2003) was used to visualise the effects of independent variables on dependent variables (R Core Team 2022). In the survival and height increment models, the fixed effects of the independent variables were allowed to vary between tree species in order to compare the field performance of pine, spruce and silver birch seedlings. Comparisons between tree species were based on statistically significant differences ($p < 0.05$) between species-specific parameters evaluated using the linearHypothesis function in the R package car (Fox et al. 2013).

The Pearson's chi-square test of homogeneity (the function chisq.test in the R package stats) was used to test for differences between tree species in the severity and symptoms of damage. Post-hoc pairwise tests between tree species were performed using the function pairwiseNominalIndependence in the R package rcompanion (Mangiafico 2023). Pairwise p-values were Bonferroni-adjusted for multiple testing.

Results

The first-year field performance by tree species

On average, the plot-level survival of spruce seedlings (96%) was higher than that of pine (93%) and silver birch (90%), whereas for healthy planted seedlings, the height increment of silver birch (26 cm year^{-1}) was higher than that of pine (9 cm year^{-1}) and spruce (10 cm year^{-1}) (Table 4).

Table 4. The first-year field performance of Scots pine, Norway spruce and silver birch on the 1000 m^2 plots of 18 regeneration experiments (the SEKAVA trial) in southern and central Finland. N = the number of plots.

Variable	N	Mean	SD	Range
Survival of planted seedlings, %[a]				
Pine	85	92.8	9.7	61.0–100.0
Spruce	158	95.6	5.5	65.9–100.0
Silver birch	70	90.3	9.1	62.4–100.0
Mean height of planted seedlings after the first growing season, cm				
Pine	85	16.4	3.1	10.5–21.2
Spruce	158	26.6	3.1	19.3–35.2
Silver birch	70	49.7	14.0	23.9–86.7
Mean height increment of healthy, planted seedlings, cm year^{-1}				
Pine	85	9.0	2.6	3.6–13.3
Spruce	158	10.3	2.8	5.4–18.7
Silver birch[b]	64	25.8	9.1	7.7–47.5
No. of pine seedlings on sowing spots	61	3.7	1.9	1.5–9.5
Success of pine seeding (at least one pine per spot)[c]	61	66.8	25.5	9.0–100.0
Success of pine seeding (at least four pines per spot)[c]	61	30.1	25.0	0.0–84.2

[a]Percentage of planted seedlings with no, minor or moderate damage.
[b]Height increment of silver birch seedlings in the first year was not measured in SEKAVA 2.
[c]Percentage of sowing spots with at least one or four pine seedlings.

Direct seeding of pine was applied on a total of 61 plots, of which 35 plots were sown to pine and 26 plots were a 50/50 mixture of pine seeding and spruce planting (Table 4). On average, two-thirds (67%) of sowing spots per plot were successfully regenerated (at least one pine seedling on the sowing spot) after the first growing season. However, the success of pine seeding varied greatly between plots (9–100%). The mean number of pine seedlings on the sowing spots of the plots was 3.7 seedlings (range 1.5–9.5). When the criterion for the successful direct seeding was at least four pine seedlings per seeding spot, less than one-third (30%) of the sowing spots per plot were successfully regenerated (Table 4).

The proportions of damage severity classes (healthy, recovery, damage or dead) were compared between pine, spruce and silver birch seedlings planted on the plots (Figure 2). Based on the homogeneity test (Pearson's chi-square, $\chi^2(6) = 1018.4$, $p < 0.001$, and Cramer's V = 0.104), the damage severity of the seedlings after the first growing season was dependent on the tree species. Spruce seedlings were the healthiest ones, followed by pine. Compared to conifers, silver birch was more susceptible to damage that affected seedling development or increased tree mortality.

Damage symptoms of planted seedlings also varied significantly between tree species ($\chi^2(14) = 2982.6$, $p < 0.001$, and Cramer's V = 0.177). Foliage loss was the most common symptom in pine, needle discolouration in spruce, and crown and top damage in silver birch (Figure 3). In most cases it was not possible to identify the causal agents, especially in the case of dead seedlings.

Model for survival of planted seedlings

The first-year survival of spruce seedlings was significantly higher than that of pine and silver birch (Table 5, Figure 4).

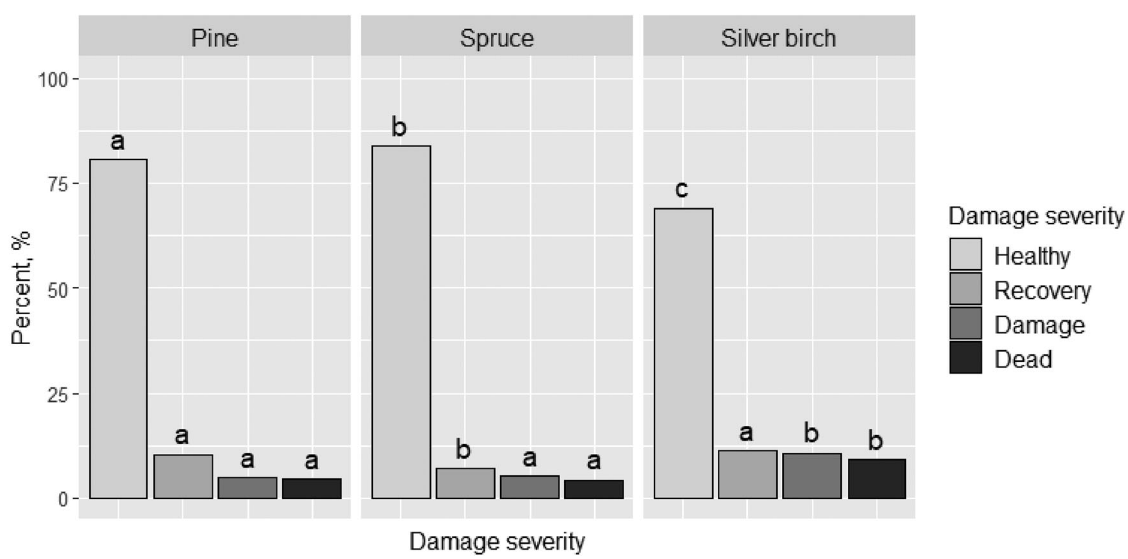

Figure 2. Proportions of damage severity classes of planted Scots pine (N = 19,247), Norway spruce (N = 19,882) and silver birch (N = 8259) seedlings after the first growing season in the SEKAVA experiments. Letters indicate the differences between tree species within the damage severity class; species-specific proportions for the same damage severity class marked with different letters are significantly different at the Bonferroni-adjusted 0.05 level.

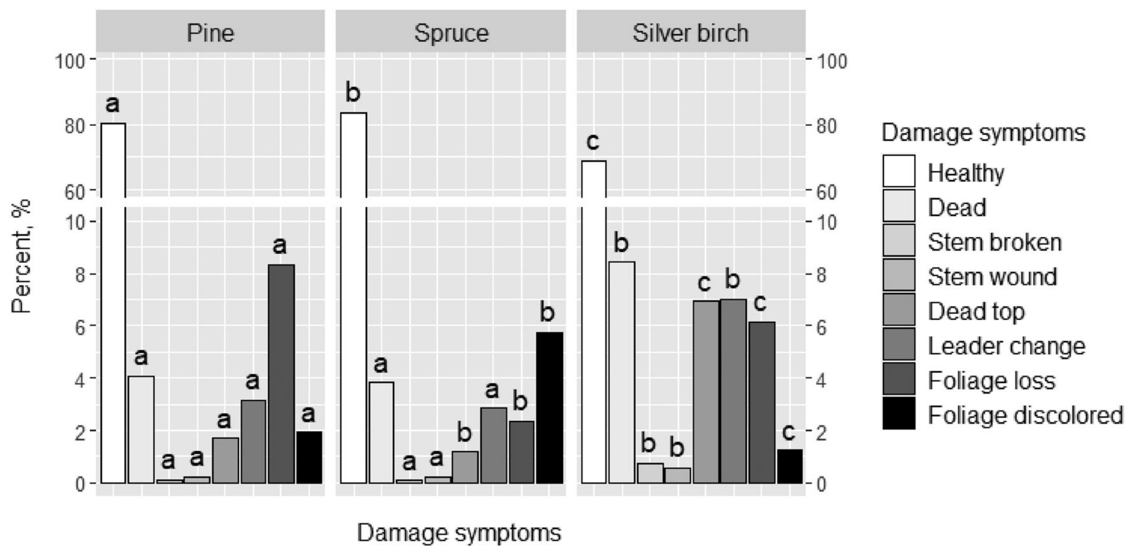

Figure 3. Proportions of damage symptom classes of planted Scots pine ($N = 19{,}247$), Norway spruce ($N = 19{,}882$) and silver birch ($N = 8259$) seedlings after the first growing season in the SEKAVA experiments. Letters describe the differences between tree species within the damage symptom class; species-specific proportions for the same damage symptom class marked with different letters are significantly different at the Bonferroni-adjusted 0.05 level.

Table 5. Parameter estimates of the multi-level quasi-binomial model estimated for the probability of first-year survival of planted seedlings on the plots of the SEKAVA experiments; only open-source variables were used as predictors. χ^2 is the joined Wald χ^2 test of the categorical fixed effects (type III test), with degrees of freedom in parentheses. The modelling data consist of 313 plot-level observations.

Fixed effects	Estimate[1]	Std err.	*t*-value	*p*-value
Intercept	0.553	0.992	0.56	0.578
Tree species:Soil texture (ref. Pine: Fine)			$\chi^2(8) =$ 69.16	<0.001
Pine: Medium	-0.378^{cd}	0.299	−1.26	0.212
Coarse	-0.544^{cd}	0.312	−1.74	0.087
Spruce: Fine	2.502^{a}	0.965	2.59	0.013
Medium	2.115^{ab}	0.977	2.16	0.035
Coarse	1.624^{b}	0.994	1.63	0.108
Silver birch: Fine	-0.913^{d}	1.043	−0.88	0.385
Medium	-0.196^{c}	1.081	−0.18	0.857
Coarse	-0.350^{cd}	1.060	−0.33	0.743
Tree species:Topographic wetness index (TWI)			$\chi^2(3) =$ 22.23	<0.001
Pine:TWI	0.456^{a}	0.128	3.57	0.001
Spruce:TWI	0.126^{b}	0.095	1.32	0.192
Silver birch:TWI	0.414^{a}	0.110	3.75	0.001
Tree species:Proportion of broadleaves[2]			$\chi^2(3) =$ 11.33	0.010
Pine:Proportion of broadleaves	-1.996^{a}	0.867	−2.30	0.026
Spruce:Proportion of broadleaves	0.753^{b}	0.715	1.05	0.298
Silver birch:Proportion of broadleaves	1.138^{b}	0.838	1.36	0.181
Random effects	Variance			
Experiment ($N = 18$)	0.877			
Plot ($N = 249$)	0.342			

[1]Species-specific estimates for the same fixed effect (i.e. soil texture, TWI, and proportion of broadleaves) marked with different letters are significantly different ($p < 0.05$).
[2]Proportion of broadleaves in volume at clearcut.

In addition to tree species, seedling survival was significantly influenced by the following open-source variables: soil texture, topographic wetness index (TWI) and the proportion of broadleaves in the volume at clearcut.

The effect of TWI on survival varied significantly between tree species ($\chi^2(3) = 22.23$, $p < 0.001$); compared to spruce, the survival of pine and silver birch responded more positively to increasing TWI. The joined effects of the interaction of tree species and soil texture on seedling survival were also significant ($\chi^2(8) = 69.16$, $p < 0.001$). Compared to medium and coarse-textured soils, the survival of conifers responded positively to fine-textured soils, whereas the survival of silver birch was the lowest on fine-textured soils (Figure 4).

The interaction between tree species and the proportion of broadleaves in the volume at clearcut was significant ($\chi^2(3) = 11.33$, $p = 0.010$). However, only the negative response of pine survival to the broadleaves proportion was significant ($p = 0.026$).

The pseudo-R^2 value of the model for the survival of planted seedlings estimated using only open-source variables was 5.1%. When the field-assessed variables were also used as predictors, the C:N ratio in the organic layer was a significant predictor ($\chi^2(3) = 19.7$, $p < 0.001$), replacing the proportion of broadleaves in the model. In the fitted model, increasing the C:N ratio in the organic layer (i.e. decreasing site fertility) significantly increased the survival of pine ($p < 0.001$) and spruce ($p = 0.034$), but did not affect the survival of silver birch ($p = 0.935$). The pseudo-R^2 value of the model including the C:N ratio in the organic layer instead of the proportion of broadleaves was slightly higher (9.7%).

Model for height increment of planted seedlings

The model for the first-year height increment was fitted for healthy, planted seedlings (Table 6). The model included the 3-way combinations of tree species, site type and soil texture as categorical variables; note that not all combinations were available in the data (e.g. silver birch was not planted on VT sites and fine textured soil was only present on OMT sites). The joined effects of the interaction of tree species, site type and soil texture on height increment were significant ($\chi^2(17) = 266.63$, $p < 0.001$). The height increment of tree species responded differently to

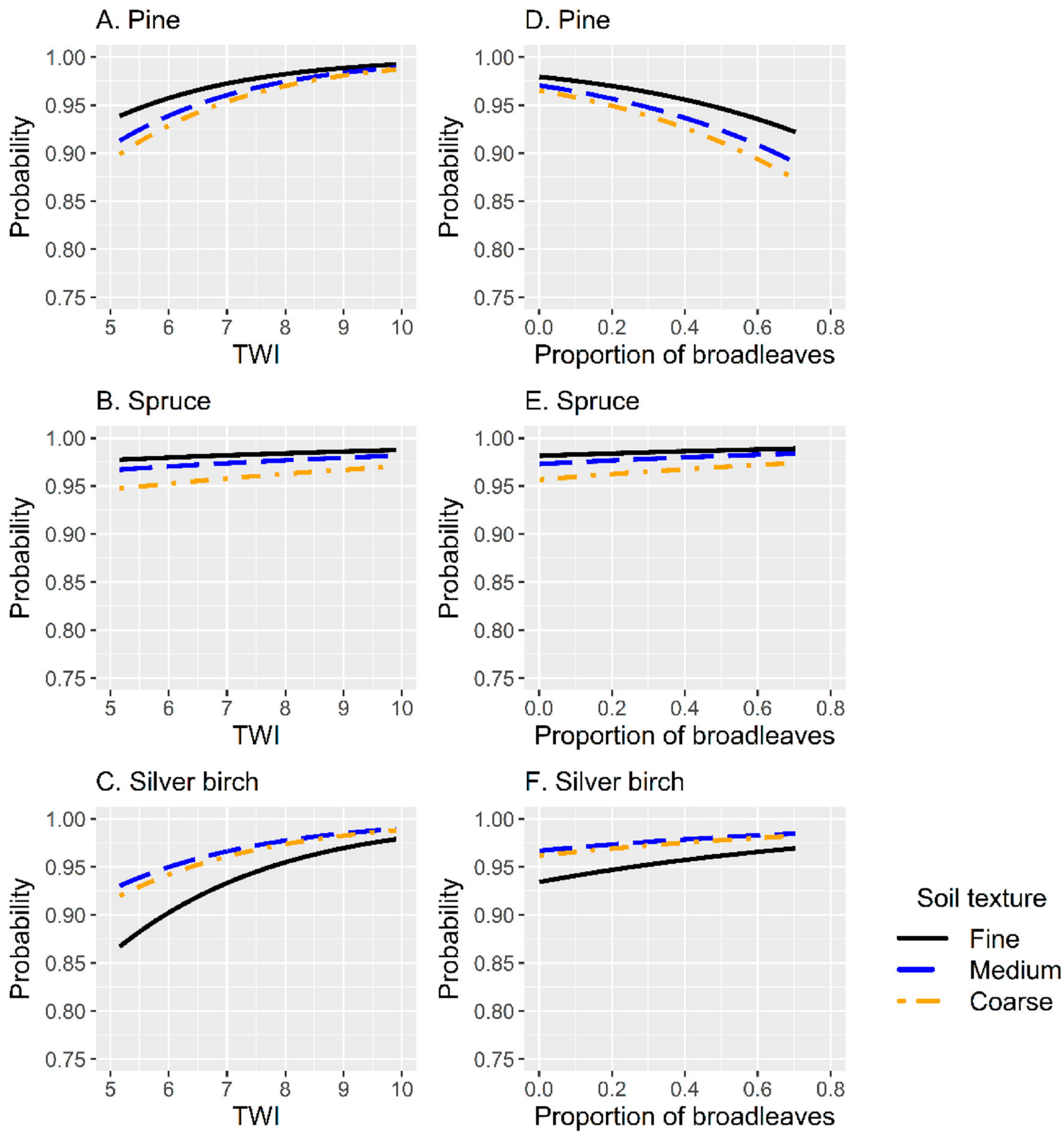

Figure 4. Predicted plot-level response of the probability of first-year survival of planted Scots pine, Norway spruce and silver birch seedlings to soil texture, topographic wetness index (TWI, Figs. A – C), and proportion of broadleaves in volume at clearcut (Figs. D – F) on the plots of the SEKAVA experiments. The soil texture and the proportion of broadleaves were obtained from the forest resources dataset of the Finnish Forest Centre. Soil texture: fine (solid), medium (long-dashed) and coarse (dot-dashed).

TWI ($\chi^2(3) = 37.20$, $p < 0.001$); the effect was positive for spruce and negative for silver birch (Figure 5), and the parameter estimate for silver birch was significantly different from that for conifers (Table 6).

On OMT and MT sites, where all tree species were planted, the height increment of silver birch was significantly higher than that of pine and spruce. On rich sites (OMT), the height increment of pine was higher on medium-textured soil than that on fine-textured soil, whereas the height increment of silver birch was higher on fine-textured soil than on coarse-textured soil (Table 6, Figure 5). For spruce on rich and rather poor sites (OMT and VT), there were no differences in height increment between soil texture classes. On medium site (MT), the height increment of spruce on coarse-textured soil was significantly lower than on medium-textured soil.

In the height increment model fitted also with the field-assessed variables, the field-assessed soil texture in the mineral soil layer of 0–10 cm ($\chi^2(8) = 81.48$, $p < 0.001$) and the C:N ratio in the organic layer ($\chi^2(3) = 48.32$, $p < 0.001$) were significant predictors and replaced the soil texture and site type variables obtained from the open datasets of the Finnish Forest Centre. The pseudo-R^2 value of the model increased from 69.0% to 72.3% when these field-assessed site characteristics were used as predictors instead of the open-source ones. In the fitted model, increasing the C:N ratio in the organic layer (i.e. decreasing site fertility) significantly decreased the height increment of pine ($p < 0.001$) and spruce ($p = 0.048$), but did not affect the height increment of silver birch ($p = 0.203$). With the field-assessed soil texture variable, the height increment of spruce was higher

Table 6. Parameter estimates of the multi-level quasi-Poisson model estimated for the mean first-year height increment of healthy, planted seedlings on the plots of the SEKAVA experiments; only open-source variables were used as predictors. χ^2 is the joined Wald χ^2 test of the categorical fixed effects (type III test), with degrees of freedom in parentheses. The modelling data consist of 307 plot-level observations.

Fixed effects	Estimate[1]	Std err.	t-value	p-value
Intercept	1.979	0.274	7.21	<0.001
Site:Tree species:Soil texture (ref. OMT:Pine:Fine)[2]		$\chi^2(17) = 266.63$		<0.001
OMT: Silver birch:Fine	1.844[a]	0.301	6.13	<0.001
Silver birch:Medium	1.675[ab]	0.315	5.32	<0.001
Silver birch:Coarse	1.279[b]	0.381	3.36	0.002
Pine:Medium	0.360[c]	0.170	2.11	0.041
Spruce:Medium	−0.151[cd]	0.321	−0.47	0.640
Spruce:Coarse	−0.267[cd]	0.363	−0.74	0.466
Spruce:Fine	−0.328[d]	0.281	−1.17	0.250
MT: Silver birch:Coarse	1.811[a]	0.301	6.02	<0.001
Silver birch:Medium	1.551[b]	0.309	5.02	<0.001
Pine:Coarse	−0.106[c]	0.099	−1.07	0.292
Pine:Medium	−0.172[c]	0.097	−1.77	0.084
Spruce:Medium	−0.396[c]	0.282	−1.40	0.168
Spruce:Coarse	−0.699[d]	0.282	−2.48	0.017
VT: Pine:Coarse	−0.292[a]	0.134	−2.18	0.035
Spruce:Coarse	−0.307[a]	0.300	−1.03	0.311
Spruce:Medium	−0.426[a]	0.304	−1.40	0.168
Pine:Medium	−0.563[a]	0.164	−3.44	0.001
Tree species:Topographic wetness index (TWI)			$\chi^2(3) =$ 37.20	<0.001
Pine:TWI	0.056[a]	0.035	1.58	0.122
Spruce:TWI	0.103[a]	0.023	4.47	<0.001
Silver birch:TWI	−0.056[b]	0.025	−2.19	0.034
Random effects	Variance			
Experiment ($N = 18$)	0.048			
Plot ($N = 246$)	0.013			

[1]Species-specific estimates for the effects of TWI as well as site-specific estimates for the interaction terms between tree species and soil texture marked with different letters are significantly different ($p < 0.05$).
[2]Soil texture and site type (OMT, MT, and VT = rich, medium, and rather poor sites, respectively) were obtained from the open-source data of the Finnish Forest Centre.

on fine-textured soils than on coarse-textured soils, while the opposite was true for silver birch.

Model for the success of direct seeding of pine

The success of direct seeding, as assessed by the proportion of seeding spots with at least one pine seedling, responded positively to TWI (i.e. moister site conditions) and to the proportion of pine in the volume at clearcut (Table 7, Figure 6). While increasing potential evaporation in July (i.e. drier weather conditions) decreased the germination and seedling emergence on sowing spots. The pseudo-R^2 value of the model for the success of direct seeding was 14.5%. No significant field-assessed site characteristics or their interactions were found when refitting the model.

When at least four pine seedlings per seeding spot were required for successful direct seeding after the first growing season, the proportion of sowing spots successfully regenerated still responded positively to TWI ($p = 0.034$) and negatively to potential July evaporation ($p = 0.046$), but the effect of the proportion of pine volume of the previous growing stock was no longer significant ($p = 0.472$).

Discussion

This study compared and analysed the responses of the first-year field performance of Scots pine, Norway spruce and silver birch seedlings regenerated in the Nordic boreal forests using detailed field measurements and open geospatial data. Based on our results, open geospatial data such as topographic wetness index (TWI), soil texture, site type and growing stock at clearcut can be used to predict species-specific early tree seedling performance and pine seeding success, and thus identify site conditions that may influence regeneration outcomes. Open geospatial data is a promising tool to support the planning of forest regeneration activities. However, the field-assessed soil texture and site fertility (here, carbon-to-nitrogen ratio) more accurately predicted the early performance of planted seedlings. The models developed were not intended to be used in practice, but follow-up data are needed to develop the tools further.

The results obtained after the first growing season are preliminary in that, for example, mortality that may occur during the winter is not yet included in the data. We recognise that field performance during the first growing season is also influenced by factors such as the nutritional status and vitality of the forest nursery seedlings, seedling handling and the quality of site preparation and planting, which were not fully controlled for in our experiments. Due to several uncontrolled and unobserved factors, the pseudo-R^2 values of our models were low, especially for seedling survival. For example, appropriate choice of planting spot and quality of planting work increase seedling growth and survival (Luoranen et al. 2018, 2022b; Wallertz et al. 2018; Pikkarainen et al. 2021; Nordin et al. 2023). Deep planting of seedlings is particularly important in mounds (Örlander 1986; Örlander et al. 1991; Luoranen and Viiri 2016; Luoranen et al. 2018, 2023). Due to e.g. stoniness and harvesting residues, the quality of planting spots varied in our experiments, and thus planting seedlings in the centre of mounds to the mineral soil cover and to the depth of 5 cm was not always possible, which may have increased seedling damage in some experiments (data not shown). In addition, the height increment of conifer seedlings is at least partly predetermined in the first years (Thompson 1976; von Wühlisch and Muhs 1986), and thus the growth in the first year was largely determined by the growing conditions in the nursery and only modified by the site and weather conditions at the planting sites.

The regeneration areas, operations and materials used in this study are representative of current forestry practices in Finland. Regeneration operations were carried out by several contractors and with different materials, which may have increased the unexplained variation between experiments. In the models, the unexplained variation between regeneration experiments was higher than the variation between plots (Tables 5 and 6), indicating that experiment-level variables describing early field performance of seedlings were still missing.

Differences were found in the early performance of planted pine, spruce and silver birch. The height increment of silver birch was higher than that of pine and spruce, and the lowest mortality rate was found in spruce seedlings (4%), followed by pine (7%) and silver birch (10%). Compared to previous studies in Finland, mortality in our study was slightly higher for all tree species. In the studies by Luoranen

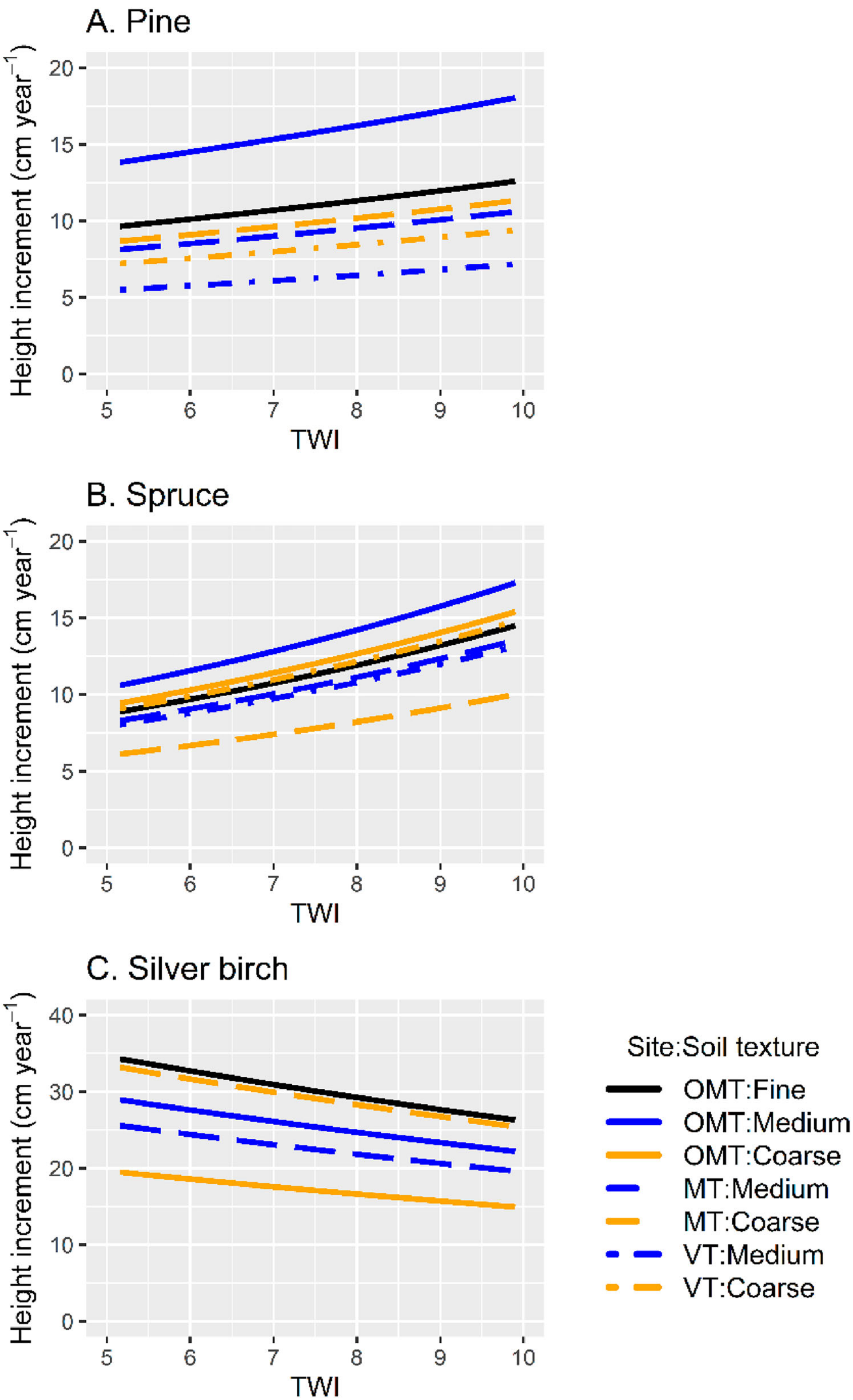

Figure 5. Predicted plot-level responses of mean first-year height increment of healthy planted (A) Scots pine, (B) Norway spruce and (C) silver birch seedlings to topographic wetness index (TWI), site type and soil texture on the plots of the SEKAVA experiments. Soil texture and site type were obtained from the forest resources dataset of the Finnish Forest Centre. Site type: OMT = rich (solid line), MT = medium (long-dashed) and VT = rather poor (dot-dashed). Soil texture: fine (black), medium (blue) and coarse (orange). Note that TWI had a non-significant effect on pine (Table 6).

and Viiri (2016) and Luoranen et al. (2022a), only 1–3% of spruce seedlings died during the first growing season in southern and central Finland. The only study that examined small, overwintered silver birch seedlings planted in spring was published by Pikkarainen et al. (2021). In their study, mortality of silver birch was 4% after three growing seasons, and mortality of pine was 2% after the first growing season. Low mortality of pine planted in mounds was also observed by

Table 7. Parameter estimates of the multi-level quasi-binomial model estimated for the proportion of sown spots that successfully regenerated (at least one Scots pine seedling per spot) during the first growing season on the plots of the SEKAVA experiments. The modelling data consist of 61 plot-level observations.

Fixed effects	Estimate	Std err.	*t*-value	*p*-value
Intercept	4.447	2.691	1.65	0.105
Topographic wetness index (TWI)	0.295	0.102	2.90	0.006
Proportion of pine in volume at clearcut	1.192	0.426	2.80	0.007
Potential evaporation in July, mm	−0.041	0.017	−2.38	0.039
Random effect	Variance			
Experiment ($N = 12$)	1.135			

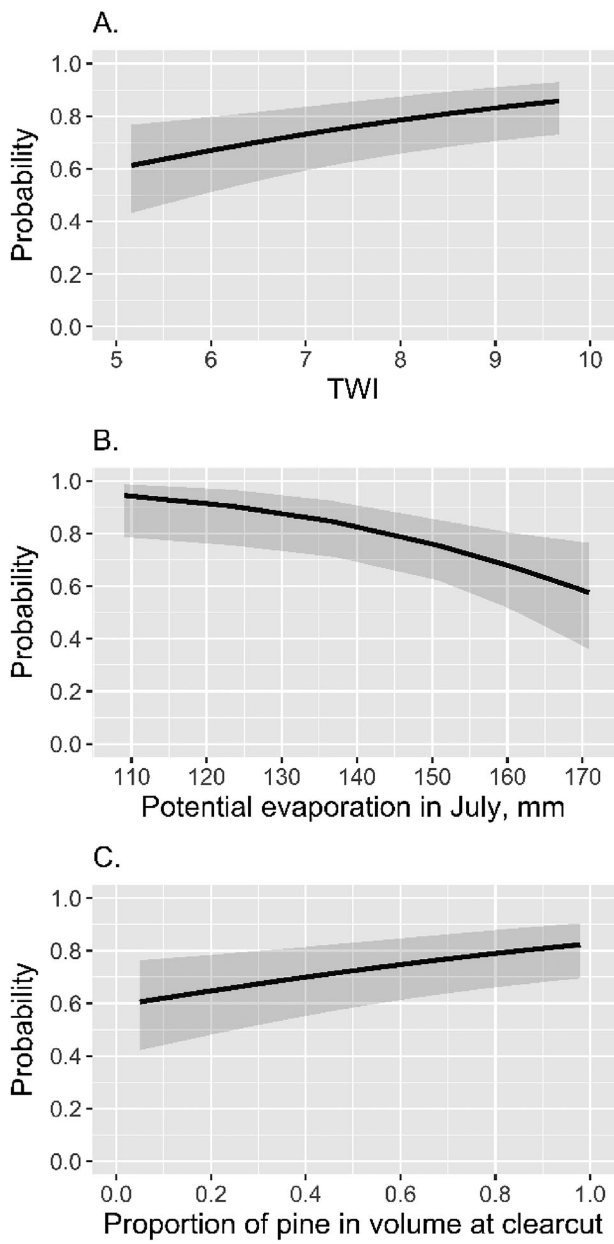

Figure 6. Predicted plot-level responses and 95% confidence intervals of the proportion of sown spots that successfully regenerated (at least one pine seedling per spot) during the first growing season to (A) topographic wetness index (TWI), (B) potential evaporation in July, and (C) the proportion of Scots pine in volume at clearcut on the plots of the SEKAVA experiments. The proportion of pine was obtained from the forest resources dataset of the Finnish Forest Centre.

Luoranen (2018), when none of the seedlings died three years after planting. Similarly, in the study by Luoranen and Rikala (2013), mortality of pine seedlings was low after the first season and 9–10% after the second season. The summer of 2021 was warm and dry, while weather conditions in 2020 and 2022 were closer to the 1991–2020 average (https://en.ilmatieteenlaitos.fi/). Ten of our experiments were planted in 2021, most of them in June. Warm and dry weather conditions may have increased the mortality, although climatic variables (or their interaction with TWI) were not significant predictors in the survival model. In the inventory by Luoranen et al. (2023), also carried out in 2021 in the same geographical area in Finland, about 6% of newly planted spruce seedlings died by the end of the first season. They also found that the mortality increased when seedlings were planted in June, especially in the later part of the month. Therefore, these exceptionally warm and dry conditions, together with rather late planting dates in one establishing year, may have contributed to the mortality.

In the recent study by Nordin et al. (2023), mortality of spruce (8%) after three growing seasons was also lower than that of pine (19%) and silver birch (42%) when seedlings were planted in mounds under different soil moisture conditions. In their study, the main causes of mortality for conifers in mounds were insects and browsing, and for silver birch fungi and browsing, and in wet areas seedlings planted outside mounds were susceptible to water logging damage. Our experiments were not established in wet areas, and seedling survival increased with increasing TWI (i.e. soil moisture).

In the present study, we were not always able to determine the agent of damage, and it was registered as unknown (cf., Johansson et al. 2015). Compared to conifers, silver birch had more crown and top damage, which may affect future seedling development or increase tree mortality. Drought was the most likely reason for crown and top damage, as it has been observed to cause drying of the top in birch (Luoranen et al. 2003) and spruce seedlings (Luoranen et al. 2023). During the first growing season after the establishment of our experiments, planted seedlings were not protected against browsing, which caused crown and top damage in silver birch. Conifer seedlings protected against pine weevil feeding were planted in our experiments, which may have reduced mortality and damage compared to the field performance of unprotected pine and spruce seedlings in the study by Johansson et al. (2015).

Species-specific early performance of planted seedlings was significantly predicted by open geospatial variables such as TWI, soil texture, site type and growing stock at clearcut. Compared to fine-textured soils, medium-textured soils favoured the survival of planted silver birch seedlings. In the study by Luoranen et al. (2003), drought damage to newly planted silver birch seedlings was more frequent on fine-textured sites than on medium-coarse sites. Planting spruce on coarse-textured soils significantly increased seedling mortality compared to fine-textured soils. Needle discolouration was a common damage symptom of planted spruce seedlings, which may indicate drought stress on coarse-textured soils (Luoranen et al. 2023). These results are logical as water holding capacity is low on coarse-textured soils, reducing the water available to newly planted seedlings and increasing the risk of drought. In addition, probably due to drought stress, the height increment of spruce seedlings planted on coarse-textured soils and dry sites (low TWI values) was lower than that of seedlings planted on fine – and medium-textured soils and moister site conditions. Our results support the silvicultural recommendations to select sites with adequate moisture and air content for silver birch planting and to avoid dry, infertile sites for spruce planting (Rantala 2011).

Pine survival responded negatively to the proportion of broadleaves in the volume at the time of clearcut. The correlation between the proportion of broadleaves and the field-assessed C:N ratio in the organic layer was negative (−0.24), suggesting that the broadleaves proportion is an indicator of the site conditions. According to Callesen et al. (2007), N concentrations and C:N ratios in Nordic forest soils vary according to dominant tree species and soil texture, and thus describing litter quality and degree of humification. In our study, increasing the C:N ratio in the organic layer (i.e. decreasing site fertility) significantly increased conifer seedling survival, but only slightly improved the performance of the survival model.

Increasing the C:N ratio in the organic layer significantly decreased the height increment of both pine and spruce. Previously, a negative correlation between height increment and C:N ratio was observed in young spruce stands, but not in pine stands (Smolander et al. 2015). In the study by Smolander et al. (2015), height increment correlated better with N concentration in the organic soil layer. In our study, the field performance of planted spruce seedlings was reduced by nutrient-poor and coarse-textured sites. However, it should be noted that regardless of soil texture, the first-year survival of spruce was significantly higher than that of pine, especially in dry site conditions (i.e. low TWI values) (Table 5, Figure 4).

In direct seeding of pine, favourable weather and soil moisture conditions were found to be important for higher seedling emergence and survival rates (Winsa 1995; Oleskog et al. 2000). Surprisingly, soil texture or its interaction with potential evaporation in July (i.e. low soil water content and high evaporation demand) did not significantly affect the success of pine seeding (cf., Kankaanhuhta et al. 2009). Sowing dates varied between experimental sites and late sowing may have reduced the success of direct seeding (de Chantal et al. 2003). In the modelling, direct seeding was considered successful if at least one seedling per seeding spot was observed at the end of the first growing season, which may overestimate the success. Seedling mortality can be high during the first winter (de Chantal et al. 2003). According to Yli-Vakkuri and Räsänen (1971) there should be at least four seedlings per seeding spot at the end of the first autumn under favourable conditions and seven seedlings per spot under unfavourable conditions. In addition to soil texture, soil moisture is also influenced by topography (Nyberg 1996). In our study, soil moisture was described by TWI, so that the success of pine seeding increased with increasing TWI. Stands previously dominated by pine were more suitable for direct seeding than stands with a high proportion of spruce or broadleaves by volume at the time of clearcut. A relatively high correlation (0.76) between the proportion of pine and the C:N ratio in the organic layer indicates that decreasing site fertility increased the proportion of pine.

Based on our results, the tree species-dominance of the previous growing stock describes the site conditions (de Chantal et al. 2003; Levula et al. 2003), especially site fertility, and could thus be used to identify the sites suitable for different tree species and regeneration methods. However, it is important to note that the growing stock of naturally regenerated, unmanaged stands at the time of clearcut may better describe site conditions than that of artificially regenerated, managed stands. In natural regeneration, specific site characteristics (e.g. soil moisture and nutrient availability) favour the emergence and establishment of different tree species, but thinning may have altered the proportion of different tree species in the growing stock. Our regeneration experiments were established in mature stands whose management history was not fully known, but all stands had been naturally regenerated and thinned during the rotation.

In the open-source forest resources data, for half of our 284 plots, site type and soil texture variables were based on information from the forest use declaration for clearcutting, and thus most likely originated from the field inventory by compartment (Koivuniemi and Korhonen 2006). For the remaining of the plots, however, open-source site variables were estimated in the MS-NFI (Mäkisara et al. 2019). In Finnish forestry, site type and soil texture are the main variables used to recommend the appropriate regeneration tree species and methods suitable for the given site conditions. Therefore, due to possible uncertainties and low spatial resolution, within-site variation in site type and soil texture should be verified by field observations. In addition, site productivity is expressed in terms of site type classes rather than species-specific site index (SI), which is defined as the height of dominant trees at a given base age. The ALS-based heights available in the forest resources data are estimated more reliable compared to tree species (especially broadleaf tree species) and stand age. Reliable estimates of the local site index would be used to identify site productivity suitable for different tree species (Saksa et al. 2021).

Using the principles of precision forestry, open geospatial data provide useful details on the site conditions suitable for growing pine and silver birch, or for selecting two or more species to create species-diverse planted forests instead of the spruce monocultures that currently dominate. Compared to planting pure spruce stands, it is relatively easy to plant or sow pine at the same time. After the first growing season, it appears that the growth rates of spruce and pine are similar and allow for similar management regimes (Bianchi et al. 2021). However, a faster initial growth rate of silver birch already in the first season indicates that mixed planting of silver birch and conifers will result in two-storey spruce-birch mixed forests, which may require a specific management programme. To establish spruce-birch mixed stands based on naturally regenerated birch seedlings, site conditions that influence the occurrence of birch admixture should be identified and taken into account (Holmström et al. 2016; Lidman et al. 2023).

This study showed that, in addition to the soil texture and site type currently used in decision making, open geospatial data such as TWI and growing stock at clearcut could be used in the selection of regeneration tree species and methods. For example, TWI could be used to avoid planting spruce on sites with a high risk of abiotic damage. These variables identified the site conditions that influenced the regeneration outcome in our experiments. Especially, if the aim is to diversify the use of tree species instead of spruce and to establish mixed forests, it is important to better identify the site conditions (e.g. site fertility and soil texture and moisture) that are suitable for different tree species and regeneration methods. However, it is important to ensure that the open data used are accurate, consistent and up-to-date, which may require field assessments.

Our results are based on the permanent regeneration experiments measured after the first growing season. It takes several years for both artificial and natural regeneration to become well established. Remeasuring the experiments, for example three years after regeneration, will allow a more thorough evaluation of early development by tree species and the preparation of new tools for practical application. Also, tree-level responses of survival and growth to different factors and their interactions need to be studied to provide more precise guidelines for ensuring successful regeneration of mixed forests.

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ORCID

Jari Miina http://orcid.org/0000-0002-8639-4383
Aura Salmivaara http://orcid.org/0000-0002-8588-8488
Karri Uotila http://orcid.org/0000-0003-4871-7564
Jaana Luoranen http://orcid.org/0000-0002-6970-2030
Saija Huuskonen http://orcid.org/0000-0001-8630-3982

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