

## Article

# Natural Regeneration of Scots Pine Requires the Application of Silvicultural Treatments such as Overstorey Density Regulation and Soil Preparation

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**Abstract:** Current management strategies for European Scots pine (*Pinus sylvestris* L.) forests are oriented towards the use of natural regeneration processes. They aim to maintain continuity of stand structure by preserving seed-producing and shelter trees at varying densities. Soil scarification techniques may be employed to support the natural regeneration of pine. Our study is based on data from seven study sites in the German lowlands, where the basal areas of the overstorey pine trees varied between 4 and 21 m<sup>2</sup>/ha. The soil scarification methods ranged from full surface ploughing by tractor or horse through small-scale scarification by cultivators to sites without soil scarification. Differences in the densities, spatial distributions, age structures, and above-ground development of pine seedlings were evaluated. We analysed the spatial interactions between overstorey pine trees and the densities of naturally regenerated pine seedlings as a function of the microsite types using the multitype Strauss hard-core process (MSH) method. The results show a significant decrease in height growth with increasing stand density after a period of 5 years, with seedling density and spatial patterns strongly influenced by soil scarification. The MSH pairwise interaction analyses revealed significant negative effects on seedling densities based on combinations of microsites and overstorey trees.

**Keywords:** *Pinus sylvestris* L.; soil scarification; seedling density; growth parameters; spatial analyses; interaction radii; multitype Strauss hard-core process



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## 1. Introduction

After a period during the 20th century in which planting was the preferred method of artificial regeneration [1], current European forest management principles focus on close-to-nature concepts supported by continuous cover forestry (CCF), primarily using natural regeneration and supporting mixed forests [2–5]. Nevertheless, for a variety of ecological and economic reasons, forest owners must always strike a balance between natural regeneration, direct seeding, and planting [6,7]. Natural pine forests (*Pinus sylvestris* L.) absent prior anthropogenic influence capable of serving as reference systems, e.g., for forest structures or age class distributions, are rare in central Europe [2,8,9]. Scots pine, a light-demanding species, typically forms mono-layered forests, but Lundqvist et al. [4] noted that there are some examples of multi-layered pine forests. Therefore, silviculturists use different crown thinning systems in Scots pine stands, such as seed tree systems, shelterwood systems, and group or strip thinning systems, aligned with planned natural regeneration [10–12]. These thinning systems differ in terms of the corresponding overstorey tree densities, their spatial distributions, and the length of the regeneration periods [13,14]. The chosen thinning system and its characteristics determine the variability in age, growth rate, and spatial distributions of pine seedlings [15,16]. Shelterwood systems with a range from 50 to 400 regularly distributed overstorey pine trees will normally lead to relatively homogenous

seedling growth, established over a longer period [17]. In contrast, seed tree systems mostly retain less than 50 overstorey trees [18], which can be distributed heterogeneously across the site [19]. All of the thinning systems mentioned provide the option to establish other tree species, in particular deciduous tree species, as admixtures [20,21].

Natural regeneration of Scots pine has a long tradition, in particular in areas where there were once high proportions of this species and suitable site conditions prevail [1,20,22]. The overall success of regeneration using natural regeneration methods is typically determined by various environmental factors [23]. Taking current climate change projections into account, it can be assumed that the influence of environmental factors will increase the uncertainty surrounding the silvicultural measures undertaken to promote natural regeneration [5,24,25]. The spatial impacts of ecological factors and the silvicultural methods determine future forest structures, influencing all stages in the life cycle of flora and fauna [2,26,27]. The first processes and development stages in the regeneration cycle in particular, such as flowering, seed production, and seed dispersal, are strongly related to weather conditions and are only indirectly controllable by silvicultural measures determining seed tree density, vitality, and spatial distributions [12,23,28]. For example, the individual growth space of overstorey pine tree crowns can be regulated continuously by crown thinning to preserve tree vitality. Such thinning methods increase the potential for flowering and seed production, but these conditions are superseded by weather conditions, such as temperature, drought, or heavy rain [29,30]. Furthermore, the dispersal of mature Scots pine seeds is strongly influenced by wind speed and wind direction [31]. It is known that the result of the anemochorous dispersal of pine seeds is spatially limited, with mean dispersal distances between 20 m and 50 m, but mostly less than 30 m [32,33]. This is also important for the evaluation process used to determine the densities of overstorey seed trees [34]. Once seeds reach the ground, overstorey trees act as a facilitative shelter against strong solar radiation and reduce direct heat or frost events, but shelter trees also compete with the surrounding ground vegetation and seedlings for water and nutrients [35]. The availability of light is only moderately reduced by the shelter of Scots pine trees compared to the conditions beneath shade-tolerant tree species [36–38]. The competition exerted by overstorey or shelter trees may impact disadvantageous types of ground vegetation like grasses or ferns, favouring pine seedlings [28]. Other identified spatial zones of influence, especially of individual overstorey pine trees, relevant for pine seedling growth and survival are root plate zones [34,39–41]. According to Karlsson & Örlander [23], it is necessary to improve our knowledge of how seed trees affect their surroundings and interact with ground vegetation and seedlings [42].

Forest practitioners use different soil scarification methods to establish suitable safe site conditions for pine seedlings by reducing the competition pressure exerted by ground vegetation [23,43,44]. The timing and choice of the soil scarification technique determine the vertical machining depth in the upper soil layer, the intensity of soil substrate mixing, and the spatial patterns of the competing ground vegetation [45]. The techniques most frequently used in forests differ in the proportions and sizes of the scarified areas. For example, cultivators establish small patches consisting of hollows and mounds [36,46–48], whereas ploughs or disc harrows pulled by horses or small tractors produce furrows and mounds across the entire stand area [14]. The proportion of the surface area that is prepared when using a cultivator with a working distance of 2 m to 3 m usually extends from 12% to 18% [47]. The creation of plough strips results in exposure of the mineral soil on 20% to 27% of the area, depending on the working width of the ploughshare and the strip spacing [36]. When plough strips are used, the exposed mineral soil can increase from 50% to 70% of the area, if the areas folded-over soil are also included in the calculation. The various soil scarification measures are used to increase seedling densities and to optimise the spatial distribution of seedlings for better growth conditions, such as increased soil temperatures and soil porosity, and altered nutrient conditions [49,50]. Small-scale heterogeneity can also be increased by the newly created microrelief [43,50].

The focus of this study is on the effects of silvicultural approaches adopted to regulate overstorey trees and microsite conditions. The following hypotheses were derived:

- (1) The most important density and growth parameters in Scots pine seedlings can be controlled by overstorey tree density or the basal area of pine stands;
- (2) Soil scarification increases pine seedling densities by reducing the competition pressure exerted by unfavourable ground vegetation types;
- (3) The small-scale patterns of varying densities of pine seedling distribution are strongly affected by the spatial distributions and interaction radii of the overstorey pine trees in combination with the prevailing ground cover species and microsite types.

## 2. Materials and Methods

### 2.1. Study Region, Sample Design and Tree Characteristics

The study was carried out in the Federal State Brandenburg, which possesses the highest proportion of Scots pine in Germany. The total area of Scots pine is 734,845 ha, representing a relative proportion of 70% of the total forest area [51]. To the north of the state, the relative proportion of pine stands is lower, at 62.5%, whereas to the south the proportion reaches 77.2%. The whole region is characterised as lowland with mostly poor and sandy soils. All of the chosen study sites were situated between 70 m and 155 m above sea level (Figure 1). The long-term annual precipitation data indicate precipitation in the northern part of the region between 607.8–642.5 mm per annum and between 603.9–670.6 mm in the southern part. The mean annual temperature is 9.0–9.4 °C in northern Brandenburg and 9.2–9.6 °C in the south [52].

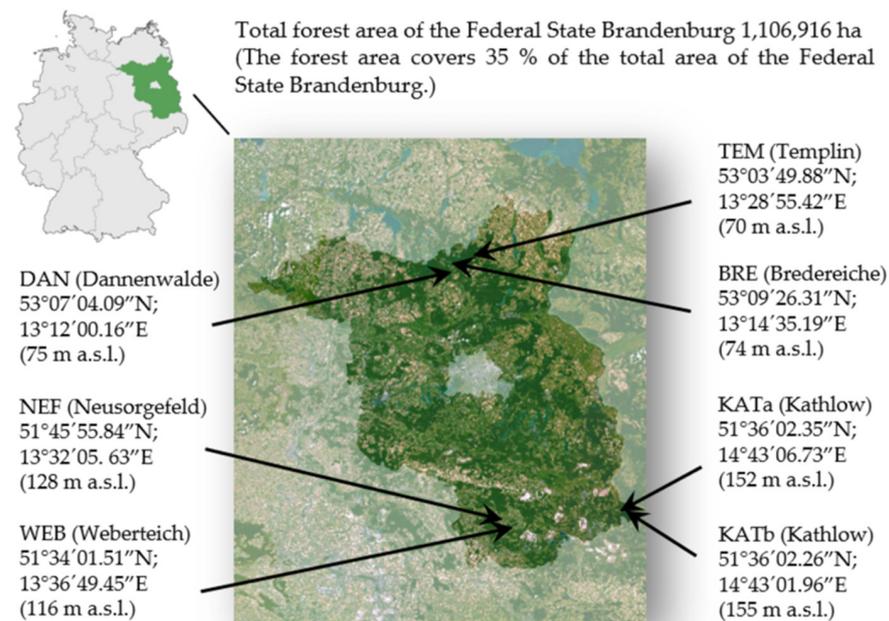
All of the chosen study sites were intensively managed and contained the skid trail systems prescribed in the silvicultural management framework directive of the Federal State Brandenburg [53]. Three pine stands were chosen as study sites in the northern part, hereafter referred to as DAN (Dannenwalde), TEM (Templin), and BRE (Bredereiche) (see Figure 1). The four study sites NEF (Neusorgefeld), WEB (Weberteich), and KATa,b (Kathlow) were representative of the forests of the southern part of the state. The chosen pine stands were characterised by mono-layered and even-aged stand structures absent other tree species. The overstorey pine trees were at least 100 years old at each site (Table 1). The stand areas ranged in size between 1.9 and 13.8 ha. Two study sites (KATa, WEB) had a tree density of fewer than 50 trees per ha, three sites (NEF, TEM, DAN) had a medium overstorey tree density (90–160 pines per ha), and on two study sites (KATb, BRE) the tree density was relatively high (230–310 pines per ha). The mean tree heights ranged between 20.2 m and 28.0 m.

**Table 1.** Overview of the stands, overstorey pine trees, and the characteristics of the study sites. (The coefficients of variation (CV) are specified in brackets and the spatial patterns are characterised by the aggregation index according to Clark & Evans (RCE)).

Parameters	KATa	KATb	WEB	NEF	TEM	BRE	DAN
stand area (ha)	4.57	8.41	1.89	6.39	3.08	3.77	13.8
number of trees (n/ha)	44	233	44	144	156	311	89
age (years)	120	120	120	125	139	128	106
basal area (m <sup>2</sup> /ha)	3.9	21.1	4.1	17.5	16.9	22.3	12.9
mean height (m)	20.5	20.2	22.1	24.9	24.8	22.0	28.0
CV of height	(0.047)	(0.712)	(0.108)	(0.056)	(0.067)	(0.096)	(0.110)
mean dbh (cm)	36.0	33.3	41.4	38.9	38.2	30.0	46.0
CV of dbh	(0.124)	(0.874)	(0.285)	(0.123)	(0.168)	(0.197)	(0.226)

Table 1. Cont.

Parameters	KATa	KATb	WEB	NEF	TEM	BRE	DAN
mean crown length (m)	8.6	5.2	8.3	8.6	13.4	7.8	11.0
CV of crown length	(0.184)	(0.697)	(0.329)	(0.317)	(0.431)	(0.221)	(0.282)
mean crown diameter (m)	5.1	3.3	2.9	5.1	6.0	3.5	6.6
CV of crown diameter	(0.242)	(0.635)	(0.338)	(0.218)	(0.204)	(0.318)	(0.332)
RCE	1.03	0.89	0.77	1.03	1.08	1.20	1.14



Examples of the three different soil scarification types



KATa (without soil scarification)



BRE (with soil scarification: cultivator)



TEM (with soil scarification: plough pulled by horses)



DAN (with soil scarification: plough pulled by tractor)

Photos: A. Wehnert (2016)

Figure 1. Locations of the study sites in the Federal State Brandenburg (Germany) and photos showing the study sites with different soil scarification types.

The measurements were done using a nested sample design with an area of 50 m × 50 m for the overstorey pine trees, whereas the pine seedlings and saplings were recorded on plots with sizes of 30 m × 30 m, with the exception of the sites BRE and DAN, which were characterised by extremely high seedling densities. There the dimensions of the regeneration plots were 15 m × 15 m. The nutrient supply of the soils may be considered poor for all study sites and the water supply moderate. Three categories of soil scarification occurred on the study sites. The first category, applied on four study sites (KATa,b, WEB, NEF), involved no soil scarification. Here the soil surface layer was dominated by typical ground cover types [42], such as undisturbed pine litter or a humus layer and ground vegetation consisting of mosses (e.g., *Dicranum scoparium* Hedw., *Pleurozium schreberi* (Brid.) Mitt., *Hypnum cupressiforme* Hedw. s. str.), grasses (e.g., *Deschampsia flexuosa* (L.) Trin., *Calamagrostis epigejos* (L.) Roth), shrubs (*Vaccinium vitis-idaea* L., *Vaccinium myrtillus* L., *Calluna vulgaris* (L.) Hull), or herbaceous plants (*Rumex acetosella* L., *Stellaria media* (L.) Vill., *Ornithopus perpusillus* L.). The second category, where the soil surface was scarified by ploughs pulled either by horse (TEM) or tractor (DAN), was represented by two sites. The study site BRE belonged to the third category of soil scarification. Here a cultivator prepared small patches 0.5 m × 1.0 m in size and to a depth of 0.10 m [47].

As a consequence of the different overstorey tree densities combined with the different soil scarification techniques, the following specific types of microsites were created: (m1) undisturbed areas within the stand dominated by ground cover, (m2) skid trails, (m3) skid trail borders, (m4) hollows or furrows, (m5) mounds, and (m6) ground cover-dominated stand edges.

To facilitate spatial analyses (see Section 2.2 below) including both overstorey trees and seedlings, the polar coordinates were measured using a laser-dendrometer (type TruPulse 360R) with a degree of precision to within 0.5° for direction and 0.2 m for distance. The polar coordinates were converted into x- and y-coordinates (Cartesian coordinates). The overstorey pine trees were characterised by parameters such as tree height, vertical and horizontal crown dimensions, and the diameter at breast height (dbh). The age was determined for all the naturally regenerated young trees. The heights of juvenile plants and their vertical and horizontal crown dimensions were recorded using a folding rule to 0.1 cm. The root collar diameter (rcd) of each plant was recorded at the soil surface with a calliper, to 0.1 mm [54]. As was mentioned, the specific ground vegetation and microsite types were recorded directly in the vicinity (5 cm radius) of each juvenile plant. Age-dependent microsite effects or interactions could be checked in this way.

## 2.2. Statistical Analyses

We analysed the age-dependent growth of pine seedlings using linear (rcd~height) and non-linear regression (age~height) models, including all trees up to 10 years of age. The relationship between the overstorey condition, represented by basal area, and seedling growth parameters, and the differences in seedling growth, were analysed using the non-parametric Mann–Whitney and Kruskal–Wallis tests [55]. The commonly used seedling growth variables slenderness, live crown ratio and crown profile facilitated further interpretation of site-specific growth dynamics [54,56].

We used spatially explicit, but relatively simple indices to adapt silvicultural measures. The reason for this was that these simple indices can be readily implemented in forest practice, and they are helpful for comparisons between different types of silvicultural management [26]. We used the widely known procedure of nearest neighbour distances to calculate the aggregation or clumping index  $R$  (hereinafter referred to as  $RCE$ ) to identify the spatial patterns of seedlings and overstorey pine trees, not only in their functions as seed sources but also as competitors of pine seedlings [57]. The aggregation index  $RCE$  was derived from the observed distance to the nearest neighbour plant ( $r_{obs}$ ) in relation to the mean estimated distance ( $r_{est}$ ) based on a random (Poisson) distribution [58].

$$RCE = \frac{\overline{r_{obs}}}{r_{est}}, 0 \leq R \leq 2.15 \quad (1)$$

The aggregation index  $RCE$  was substantiated by the following scale for interpretation [57,59]:  $RCE = 1$  (random distribution),  $RCE < 1$  (aggregated or clumped distribution),  $RCE$  close to 0 (strongly aggregated or clumped distribution),  $RCE > 1$  (regular distribution), and  $RCE$  close to 2.15 (strongly regular distribution). We calculated the individual growth space of pine seedlings using Delaunay triangulation and the centroidal Dirichlet or Voronoi tessellation (hereinafter referred to as TESS) using Lloyd's algorithm as part of the r-package 'deldir' [60]. Our analysis tested the assumption that an increase in seedling density leads to an immediate reduction in the growing space occupied by individual seedlings. However, detailed information about different spatial scales is missing from the aforementioned spatial indices [26,61]. Point pattern analyses and related model approaches were applied to accommodate for this (see below).

### 2.2.1. Point Pattern Analysis

The general technique used to describe the spatial patterns of pine regeneration was spatial point process analysis [62–64]. A prerequisite for analyses of this kind is a common observation window (see description of plots) for the different data, e.g., point data of old pine trees, of seedlings, and covariates. The covariates measured to describe the environmental conditions confronting the seedlings were the microsite types described before (six classes m1–m6, see Section 2.1). The information about the microsite types was taken from the seedlings' locations and spatial smoothing was performed. As the microsite information is categorical, the bandwidth was set to zero when smoothing. Thus, kernel smoothing becomes mathematically equivalent to nearest-neighbour interpolation. The smoothed information was stored in image files.

### 2.2.2. Modelling

In spatial point pattern statistics, the terms 'intensity' and point 'density' are both used to characterise the number of points per unit of area (p. 175 [62]). Prior to modelling the density of pine seedlings, the spatial point pattern of the pine seedlings as such had to be described. The effects of the covariate and the interaction between overstorey pine trees and seedlings were assessed individually.

The density of pine seedlings was determined using the following equation (p. 80 [62])

$$\hat{\lambda} = \frac{N(W)}{\nu(W)} \quad (2)$$

where  $N(W)$  is the number of pine seedlings in the observation window and  $\nu(W)$  is the area of the window. In addition to the question of mean pine seedling densities, our analyses addressed the spatial patterns of pine seedlings throughout the window.

Modelling pine seedling intensity to test our hypotheses (see introduction), we assumed the individual point process of a single plot to be inhomogeneous, or non-stationary. We sought to analyse a spatial trend caused by environmental covariates (microsite types) and by the effect of the overstorey pine trees on the seedlings. We did not account for an internal process of clustering within the seedling cohort, i.e., point interaction. However, inhomogeneity and clustering may be related [64].

In each plot, the intensity  $\lambda$  is inhomogeneous across different locations but is a different, random value in different plots. We assumed that the log-intensity is a normal random variable.

An important step in the analysis of a non-stationary point process is building a function ' $\rho$ ', which provides information on how the intensity of points depends on the value of a covariate, e.g., ' $Z$ '. Thus,

$$\lambda(u) = \rho(Z(u)) \quad (3)$$

where  $Z(u)$  is the value of the covariate at the location  $u$ .

As we attempted to assess the effect of both the covariate ‘microsite type’ and of the overstorey pine trees on the seedling intensity simultaneously, we understood the underlying process to be a Gibbs point process. Gibbs point processes are an important model class that exhibits dependence between points (chapter 13 [64]). They are typically best suited to modelling spatial inhibition (pp. 138, 157, 171 [62]). In our case, the interaction between the points, i.e., between the positions of the old pine trees and the positions of the pine seedlings, is crossed, meaning that we aimed to model dependence between two types of points in a multitype spatial point process. We chose the ‘multitype Strauss hard-core point process model’ (MSH) as a hybrid of the multitype Strauss process (MS) and the multitype hard-core process (MH) to represent the interaction.

The model was evaluated within a generalised linear model (GLM) framework with the intensity function

$$\lambda(u|\mathbb{X}) = e^{\eta^T Z(u) + \varphi^T T(u, \mathbb{X})} \quad (4)$$

with  $\lambda(u|\mathbb{X})$  being the conditional intensity and  $\mathbb{X}$  a spatial point process. The function  $Z(u)$  is specified by the trend formula and  $T(u, \mathbb{X})$  is specified by the interaction argument.  $\eta$  and  $\varphi$  are canonical parameters.

In a multitype Strauss hard-core point process model (MSH) it is necessary to specify the irregular or nuisance parameters such as the pairwise interaction distance. The interaction distance of the Strauss part of the model was given by prior knowledge, taking into account the fact that the statistical theory for estimating such parameters is not really clear (p. 516 [64]). We assumed an interaction distance of 2.5 m, which is roughly the lower limit used in previous modelling of the effects of overstorey pine trees on regeneration, and corresponded to the mean crown radius of the overstorey pine trees in all our study sites [34,65]. The pairwise interaction parameter of the multiple hard-core process (MH), however, was estimated using the maximum profile pseudolikelihood method (p. 518 [64]). Computations were performed using the package ‘spatstat’ (2.2-0) in R (4.1.1).

### 3. Results

#### 3.1. Densities and Growth Characteristics of Pine Regeneration

The seedling densities ranged between 5900 and 199,070 plants per hectare, with higher densities recorded on the study sites TEM, BRE, and DAN, where soil scarification occurred. The overarching consideration of microsite types across all stand types and age groups of seedlings revealed only weakly significant differences between seedling densities (Kruskal-Wallis,  $df = 5$ ,  $p \leq 0.49$ ). Mean seedling age values of between 5 and 8 years were recorded on five study sites. Only on the sites BRE and DAN were the seedlings considerably younger (Table 2). However, the coefficient of variation illustrates the highest variations of seedling ages on the sites KATb, BRE, and NEF. The maximum proportion of seedlings older than 10 years was 13.2% on the site NEF.

**Table 2.** Mean values and coefficients of variation (in brackets) of total pine seedling densities, separated by microsite types (m—microsite, m1—stand conditions without soil scarification, m2—skid trail, m3—skid trail border, m4—hollows or furrows, m5—mounds, m6—stand edge).

Parameters	KATa	KATb	WEB	NEF	TEM	BRE	DAN
total seedling density (n/ha)	5900	7844	12,089	10,589	35,856	87,511	199,067
proportion of pine seedlings with an age up to 10 years (%)	93.2	93.6	99.3	86.8	96.6	100.0	100.0
m1 seedling density (n/ha)	4222	1967	11,489	5789	29,244	24,000	-
m2 seedling density (n/ha)	1033	4500	533	3967	4300	27,378	-
m3 seedling density (n/ha)	-	1378	33	833	2300	9911	-

Table 2. Cont.

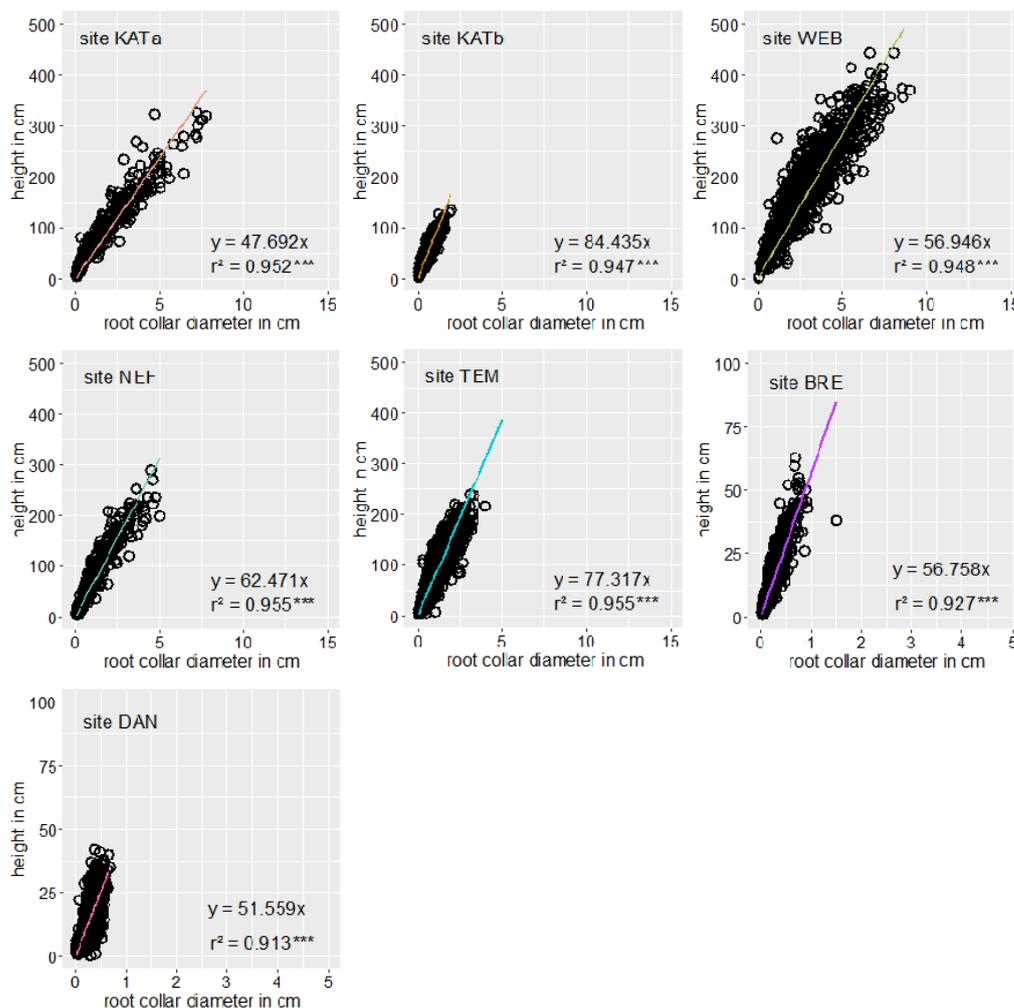
Parameters	KATa	KATb	WEB	NEF	TEM	BRE	DAN
m4 seedling density (n/ha)	-	-	-	-	-	22,622	105,422
m5 seedling density (n/ha)	-	-	-	-	-	3600	93,644
m6 seedling density (n/ha)	644	-	33	-	-	-	-

Due to their higher mean ages, the seedlings at the site WEB had the highest values of the growth parameters height, rcd, crown length, and diameter, followed by the seedlings on site KATa (Table 3). Pine seedlings there exhibited higher growth than the seedlings on the sites KATb and TEM with comparable mean ages. The pine seedlings on the sites KATb and TEM were characterised by higher mean values of slenderness, 10.47 and 8.20, respectively, whereas live crown ratios were highest on the sites KATa (64%) and WEB (67%).

**Table 3.** Mean values and coefficients of variation (CV in brackets) of the growth characteristics of pine seedlings (slenderness (height/rcd), live crown ratio (crown length relative to tree height), crown profile for all trees with established branches (crown length/crown diameter)).

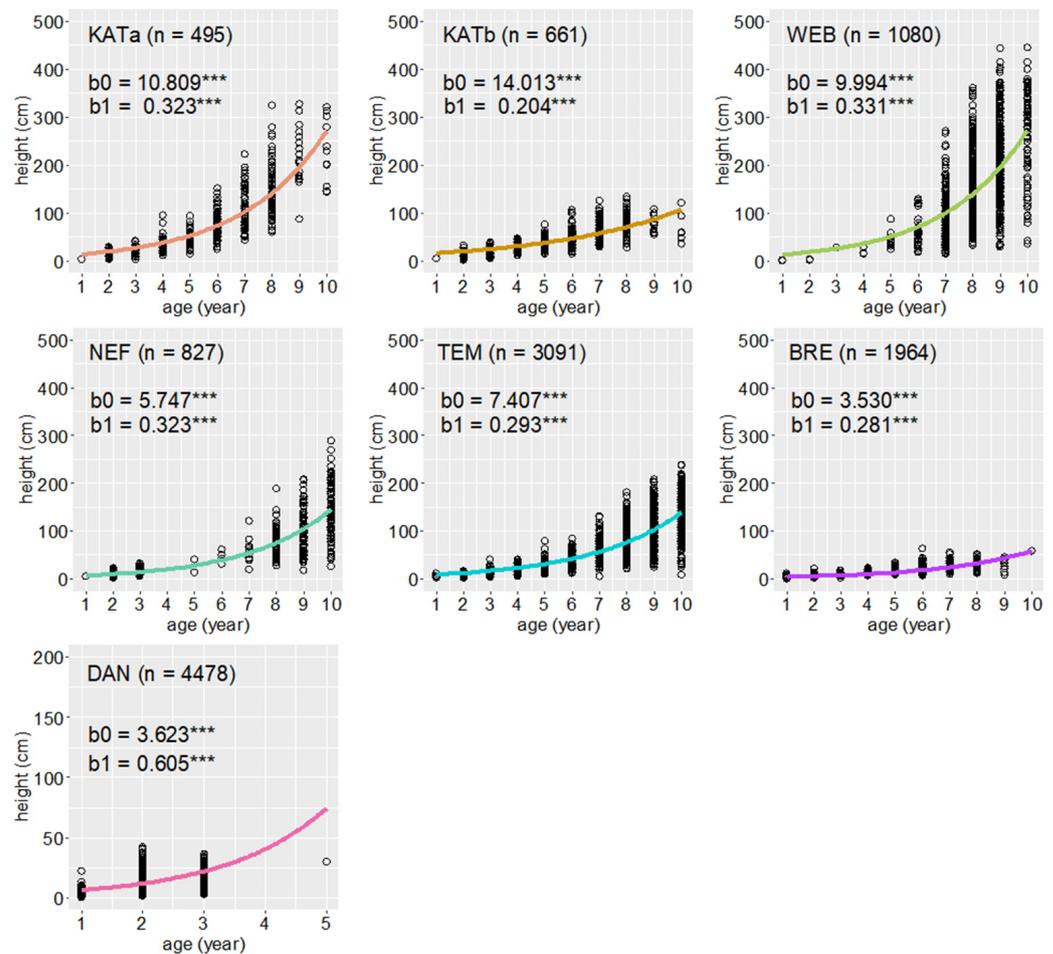
Parameters	KATa	KATb	WEB	NEF	TEM	BRE	DAN
mean age (years)	6.14	6.85	8.16	5.39	7.32	2.02	1.51
CV of age	(0.443)	(0.983)	(0.178)	(0.714)	(0.347)	(0.983)	(0.349)
mean height (cm)	97.40	59.59	158.16	63.72	77.25	7.44	10.37
CV of height	(0.925)	(1.321)	(0.582)	(1.206)	(0.668)	(1.177)	(0.761)
mean rcd (cm)	1.892	0.705	2.575	1.000	0.97	0.13	0.20
CV of rcd	(1.134)	(1.553)	(0.695)	(1.327)	(0.726)	(1.088)	(0.847)
mean crown length (cm)	85.13	37.76	115.48	73.84	52.18	14.19	13.38
CV of crown length	(0.994)	(1.186)	(0.703)	(0.923)	(0.718)	(0.639)	(0.498)
mean crown diameter (cm)	55.891	26.34	75.79	53.92	41.21	10.18	5.95
CV of crown diameter	(0.987)	(1.210)	(0.624)	(0.849)	(0.659)	(0.710)	(0.476)
mean slenderness	7.07	10.47	6.83	7.51	8.20	5.64	6.21
CV of slenderness	(0.444)	(0.361)	(0.353)	(0.348)	(0.300)	(0.341)	(0.558)
mean live crown ratio	64.44	49.60	67.38	39.50	54.22	54.86	37.29
CV of live crown ratio	(0.413)	(0.488)	(0.285)	(0.879)	(0.668)	(0.348)	(1.100)
mean crown profile	2.30	2.63	1.58	1.65	1.40	2.01	2.69
CV of crown profile	(1.588)	(2.007)	(0.524)	(0.983)	(0.438)	(1.069)	(0.632)

The crown profile values showed that for all pine seedlings, the crown lengths were higher than the crown diameters, but this relationship was particularly pronounced on the sites KATb (2.6) and DAN (2.7). The relationships between rcd and seedling height could be described as highly significant ( $p$ -value  $\leq 0.000$ ) by linear functions (Figure 2). As was mentioned for the variable slenderness, the increase to the total seedling height represented by the linear function was highest for pine seedlings on site KATb ( $a = 84.435$ ,  $r^2 = 0.947$ ,  $p$ -value  $\leq 0.000$ ), followed by site TEM ( $a = 77.137$ ,  $r^2 = 0.955$ ,  $p$ -value  $\leq 0.000$ ).



**Figure 2.** Linear models to show the relationships between the root collar diameter (cm) and height (cm) of pine seedlings up to an age of 10 years (signif. code: 0 '\*\*\*'). Note the different scales for the sites BRE and DAN.

The age-dependent height growth functions (Figure 3) were highly significant ( $p$ -value  $\leq 0.000$ ) for pine seedlings between 1 and 10 years of age on all study sites. The slopes of the curves characterise the steep increase of height growth on the sites KATa and WEB. After 10 years of development, juvenile pines on these two sites reached mean heights of 230 cm and 257 cm, respectively. In contrast, pine seedlings on the site BRE exhibited a very low increase in height growth with increasing age. This becomes clear based on the significant differences between the heights of pine seedlings older than 5 years on the site BRE compared to all other study sites (Mann-Whitney test,  $p$ -values  $\leq 0.001$ ). One-year-old seedlings exhibited comparable height growth across all study sites (Mann-Whitney test,  $p$ -values  $> 0.05$ ). It appears that seedlings of the same study site exhibit greater variation in their individual height growth with increasing age (Figure 3).



**Figure 3.** Age-dependent height growth functions for Scots pine up to an age of 10 years depicted separately for each site (non-linear regression model, nls model:  $\text{height.cm} \sim b_0 \times \exp(b_1 \times \text{age})$ ). Note the different scale for the site DAN.

It could be demonstrated that most of the variables relevant for pine seedling growth were directly correlated with the basal area of the overstorey pine trees. These correlations become effective with pine seedling ages of 5 years and upwards, as shown in Table 4.

**Table 4.** Results of Pearson's correlation analyses of overstorey trees (basal area (BA),  $\text{m}^2/\text{ha}$ ) and age-dependent seedling parameters (h—height in cm, rcd—root collar diameter in cm, crown length in cm, crown diameter in cm).

Age	BA~Height		BA~rcd		BA~Crown Length		BA~Crown Diameter		BA~Slenderness	
	r	p-Value	r	p-Value	r	p-Value	r	p-Value	r	p-Value
1	−0.582	0.171	−0.585	0.167	NA	NA	NA	NA	0.386	0.392
2	−0.607	0.202	−0.052	0.912	−0.150	0.810	−0.953	0.196	0.269	0.559
3	−0.707	0.075	−0.039	0.934	−0.465	0.353	−0.125	0.875	−0.083	0.876
4	−0.443	0.455	−0.449	0.448	−0.329	0.589	−0.357	0.555	−0.258	0.674
5	−0.833	0.039	−0.920	0.009	−0.895	0.016	−0.947	0.004	0.172	0.712
6	−0.869	0.025	−0.916	0.010	−0.863	0.027	−0.887	0.018	0.416	0.412
7	−0.904	0.013	−0.901	0.014	−0.877	0.022	−0.884	0.020	0.342	0.507
8	−0.969	0.001	−0.954	0.003	−0.955	0.003	−0.949	0.004	0.504	0.308
9	−0.980	0.001	−0.970	0.001	−0.971	0.001	−0.957	0.003	0.547	0.261
10	−0.975	0.001	−0.994	0.000	−0.991	0.000	−0.979	0.001	0.872	0.023

The strength of the correlation and the level of significance increased concurrently with increasing ages of the seedlings. The slenderness of pine seedlings was significantly correlated with the basal areas of overstorey trees only for pine seedlings 10 years of age.

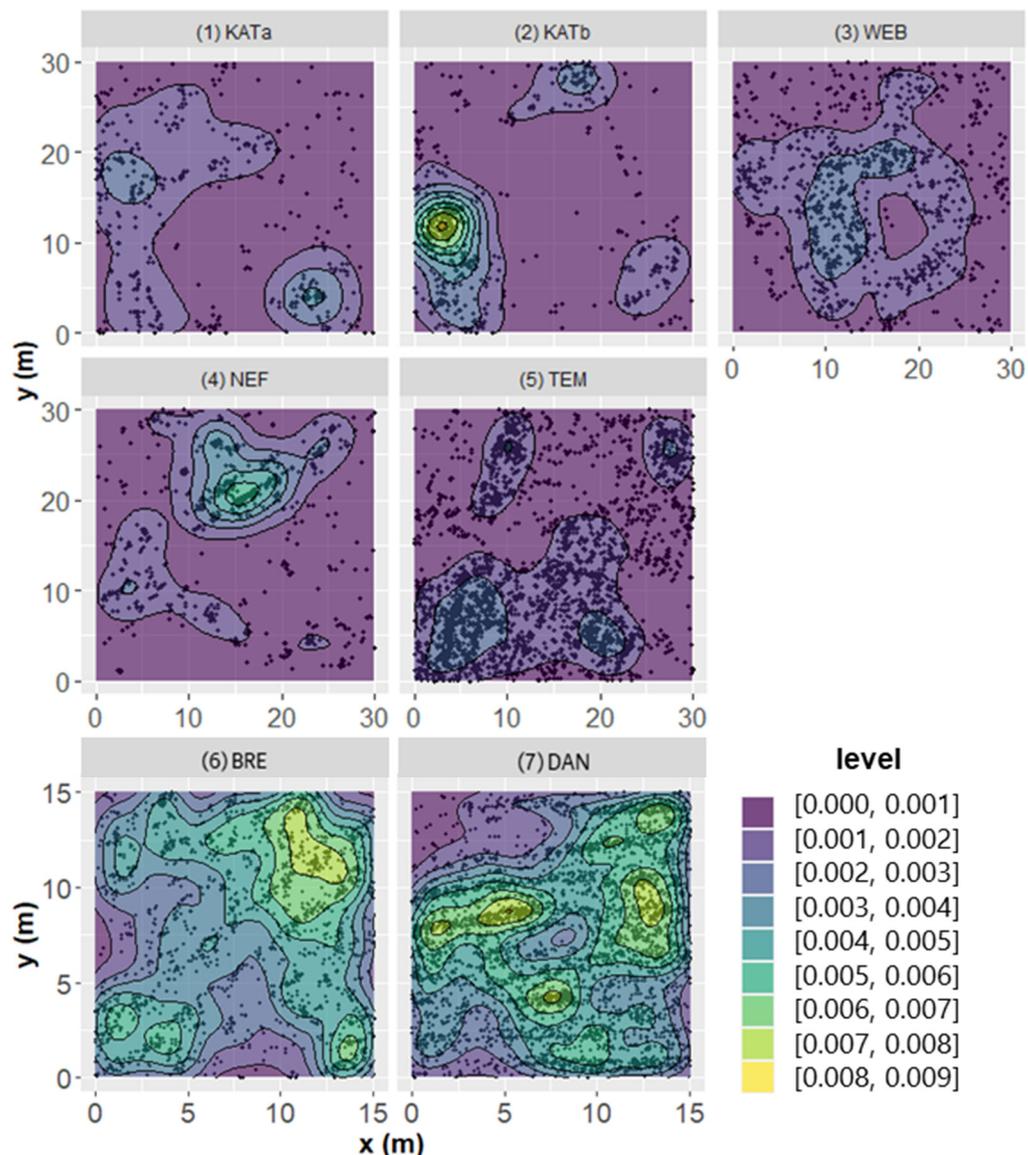
### 3.2. Density, Spatial Distribution and Growth of Pine Seedlings Relative to Ground Vegetation and Microsite Type

It was assumed that the establishment of pine seedlings and their spatial distributions are determined by overstorey trees, microsite conditions, and natural processes. The small-scale spatial patterns of pine seedling densities on the sites reflected the courses of skid trails and the particular soil scarification technique (Figure 4). The frequency and seedling-related proportions of microsite types differed between the study sites in spite of comparable stands or soil preparation. The most frequent vegetation types representing the typical microsite type in zones without soil scarification were pine litter (77.0%) and mosses (59.5%). The sites without soil scarification were dominated by *Vaccinium vitis-idaea* (42.5%) and *Vaccinium myrtillus* (31.4%). More than 90% of the pine seedlings on the site BRE grew in pine litter, in moss on site TEM and amongst *Vaccinium spec.* on site KATb. The highest coverages of mosses were recorded on the sites KATb (67.7%), NEF (62.3%), and TEM (62.0%). The ground cover around seedlings on the site DAN was predominately mineral soil (59.8%). The highest proportions of pine litter cover were observed on the sites WEB (62.4%) and KATa (50.6%). Pine seedlings were found only sporadically amongst all of the other vegetation types, at proportions of between less than 1% and 9%.

The calculated *RCE* confirmed the basic tendency to aggregated/clumped pine seedling distributions on all study sites, with all microsite types included. The strongest aggregations, with a *RCE* of approximately 0.6, were identified for the sites KATa, KATb, and NEF without soil scarification (Table 5). The lowest tendency towards seedling aggregation (*RCE* = 0.8) was found on site DAN, where the soil was scarified over the entire area using a plough pulled by a tractor. The resulting *RCE* values show strongly aggregated seedling distributions (*RCE* 0.2–0.3) along skid trails (m2, m3), stand edges (m6), and on the small hollows or mounds created by the cultivator (m4, m5) on site BRE (Table 5).

**Table 5.** Calculated aggregation indices (*RCE*) and mean growth spaces (TESS) per pine seedling (all ages included) separated by microsite type (m—microsite, m1—stand conditions without soil scarification, m2—skid trail, m3—skid trail border, m4—hollows or furrows, m5—mounds, m6—stand edge) for each study site. All *RCE* values are highly significant.

Microsite Types	Indices	KATa	KATb	WEB	NEF	TEM	BRE	DAN
m1	<i>RCE</i>	0.581	0.537	0.746	0.578	0.702	0.526	-
	TESS	2.746	3.659	0.982	1.810	0.403	0.239	-
m2	<i>RCE</i>	0.236	0.346	0.237	0.228	0.265	0.357	-
	TESS	1.063	1.015	1.719	0.521	0.283	0.108	-
m3	<i>RCE</i>	-	0.351	0.033	0.258	0.204	0.326	-
	TESS	-	1.551	12.806	0.905	0.447	0.170	-
m4	<i>RCE</i>	-	-	-	-	-	0.302	0.517
	TESS	-	-	-	-	-	0.139	0.045
m5	<i>RCE</i>	-	-	-	-	-	0.316	0.742
	TESS	-	-	-	-	-	0.191	0.101
m6	<i>RCE</i>	0.236	-	0.035	-	-	-	-
	TESS	2.270	-	9.073	-	-	-	-
total	<i>RCE</i>	0.598	0.595	0.770	0.573	0.736	0.684	0.810
	TESS	2.401	1.777	1.065	1.271	0.392	0.163	0.071



**Figure 4.** Spatial distribution and densities (level) of pine seedlings on the different sites.

The mean growth spaces occupied by individual pine seedlings revealed tendencies toward certain site and microsite conditions. The growth spaces of individual pine seedlings were very small on the sites DAN and BRE. Pine seedlings on the sites KATa and KATb occupied the largest mean growth space per seedling. The linear regression models revealed significant relationships between the growth space occupied and the overall growth of pine seedlings (Table 6). An increase in the values of the various growth parameters led to an increase in individual seedling growth spaces and vice versa.

Taking into account the fact that microsite type affects the early growth of pine seedlings, the results of the statistical analyses underlined the significance of the differences in pine seedling development between microsite types (Kruskal-Wallis,  $df = 5$ ,  $p \leq 0.000$ ).

Further analyses of microsite type without scarification (m1) revealed that only on pine litter did the density of pine seedlings decrease significantly with an increasing basal area of the overstorey pine trees ( $a = -1.323$ ,  $b = 59.076$ ,  $r^2 = 0.734$ ,  $p$ -value = 0.029). The more age-specific analyses illustrated significant relationships between the ground vegetation or ground cover types as part of m1 and the presence of pine seedlings (Table 7). The linear regressions were used to check the relationships between seedling age and the cover of the most frequent ground cover types as part of m1.

**Table 6.** Growth space of individual seedlings calculated by tessellation in relation to seedling growth parameters; all study sites included.

Functions	Estimate	Std. Error	t-Value	Adj. r <sup>2</sup>	p-Value
lm(age~tess.area-1)	1.072	0.253	4.23	0.424	0.000
lm(height~tess.area-1)	13.323	3.188	4.18	0.417	0.000
lm(rcd~tess.area-1)	2.487	0.521	4.77	0.486	0.000
lm(crown.diameter~tess.area-1)	6.811	1.553	4.39	0.442	0.000

**Table 7.** Relationships between the proportion of different ground cover types and pine seedling age; all study sites included.

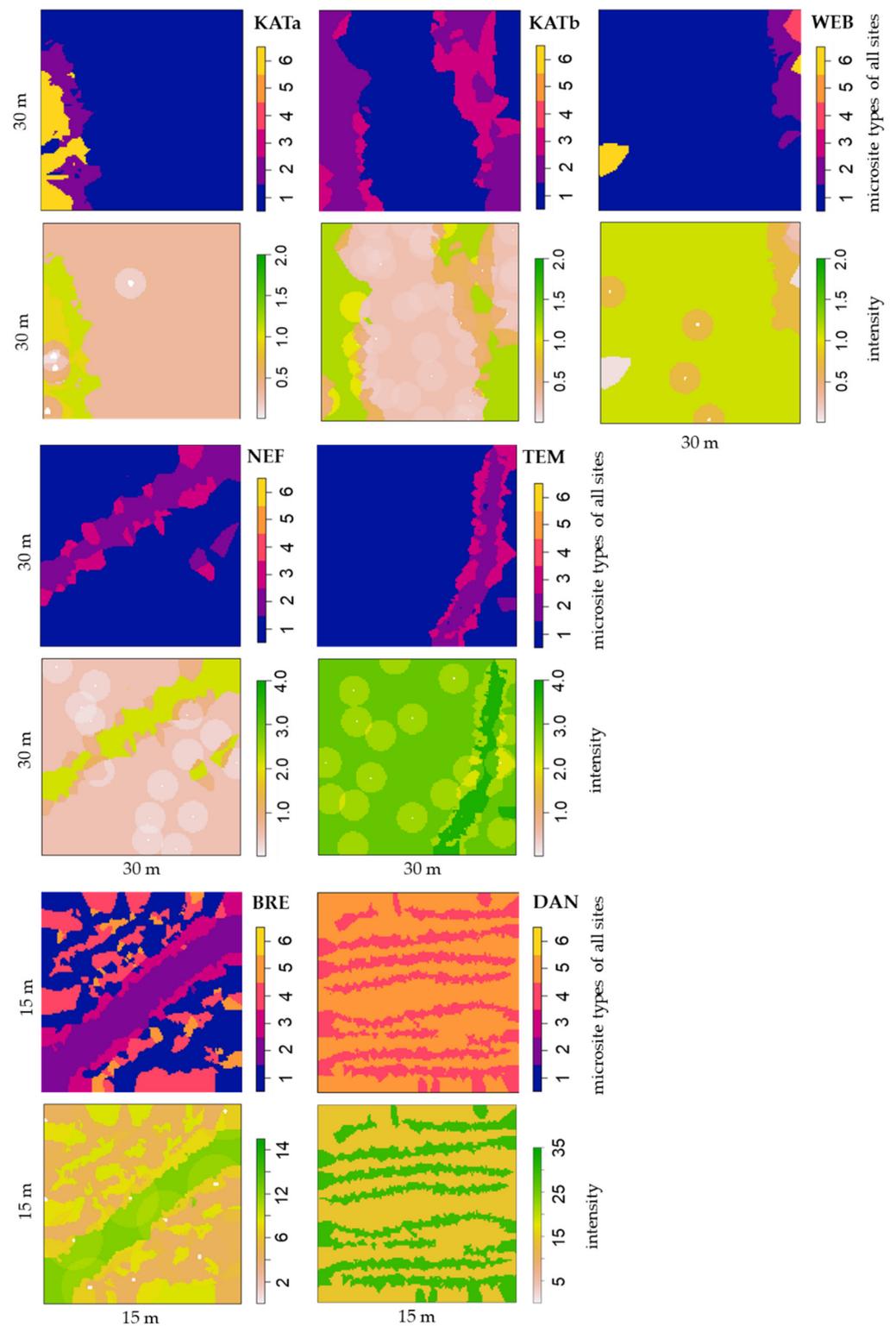
Function	Estimate	Std. Error	t-Value	Adj. r <sup>2</sup>	p-Value
lm(pine.litter~age-1)	6.016	0.434	13.880	0.771	0.000
lm(moss~age-1)	7.770	0.803	9.680	0.623	0.000
lm(vaccinium.vitis~age-1)	2.638	0.294	8.965	0.582	0.000
lm(vaccinium.myrt~age-1)	2.901	0.267	10.850	0.672	0.000

The proportion of moss as ground cover type decreased significantly with the increasing age of the pine seedlings, whereas the cover of pine litter and both *Vaccinium* species increased with increasing seedling age.

### 3.3. Effects of Overstorey Trees and Microsite Conditions on Regeneration Density

The final step in the analysis was to combine the effects of overstorey trees and the six microsite types (m1 to m6) determining the presence of pine seedlings on small spatial scales. The following maps generated from the empirical microsite information illustrate the individual spatial distributions of microsite types for each study site (Figure 5).

The graphic displays an extensive expanse of areas without scarification (m1) on the sites KATa, KATb, WEB, NEF, and TEM, with some patches characterised by stand edge conditions and skid trails. The highest spatial heterogeneity of microsite types was found on site BRE, scarified by the cultivator. The microsite structure on site DAN was clearly divided into linear courses of furrows (m4) and mounds (m5) as a result of scarification by the plough. Significant interactions between overstorey pine trees and different growth parameters of pine seedlings were already demonstrated (see Section 3.1, Table 4), but to prove the relationships on a spatial level we applied different pairwise interaction functions (see Table 8). The intensities of overstorey pines and pine seedlings ranged between values of 0.004 and 0.03, and 0.49 and 15.8, respectively. Different radii were applied in the two functions to represent interaction. In the non-stationary multitype Strauss (MS) process a value of 2.5 m was applied for all study sites (see methods). The interaction radii of the multitype hard-core (MH) processes were estimated to much smaller values between 0.1 m and 0.5 m using the maximum profile pseudolikelihood method.



**Figure 5.** Maps showing the spatial patterns of microsite types on each study site (microsite types: m1—stand without soil scarification, m2—skid trail, m3—skid trail border, m4—hollows or furrows, m5—mounds, m6—stand edge). Visualisation of the results of multitype Strauss hard-core process (MSH) calculations showing the spatial effects of overstorey pine trees and different microsite types on pine seedling densities. Note the different scales of intensities.

**Table 8.** Calculations with optimised radii, interaction radii of non-stationary multitype Strauss (MS) and multitype hard-core (MH) processes, and calculated frequencies, proportions, and intensities of overstorey pine trees and seedlings ( $\leq 10$  years).

Site	MS Radii (m)	MH Radii (m)	Overstorey Pine Trees			Pine Tree Regeneration		
			Freq.	Proportion	Intensity	Freq.	Proportion	Intensity
KATa	2.5	0.50	4	0.00739	0.00394	501	0.99208	0.49342
KATb	2.5	0.11	32	0.04261	0.03167	674	0.95467	0.66694
WEB	2.5	0.26	5	0.00419	0.00499	1080	0.99539	1.07853
NEF	2.5	0.10	14	0.01665	0.01421	827	0.98335	0.83937
TEM	2.5	0.10	17	0.00543	0.01661	3113	0.99457	3.04099
BRE	2.5	0.17	10	0.00505	0.03444	1969	0.99495	6.78124
DAN	-	-	2	0.00044	0.00693	4579	0.99956	15.87229

The following graphs depicting overstorey tree effect zones (Figure 5) underline the results of the multitype Strauss hard-core process calculations (MSH) in Table 9. These effects were particularly evident on study sites with few trees (KATa, WEB, and NEF). With the exception of the site WEB (Table 9), the skid trail microsite type (m2) exhibited the highest pine seedling intensities compared to all the other microsite types (m1, m3 to m6). The parameters of the hollows or furrows microsite type (m4) revealed higher seedling intensities than for the mounds microsite type (m5) on the scarified sites DAN and BRE.

**Table 9.** Parameters of the calculated multitype Strauss hard-core process (MSH) (m—microsite, m1 (intercept)—stand conditions without scarification, m2—skid trail, m3—skid trail border, m4—hollows or furrows, m5—mounds, m6—stand edge, markX1xX2—interaction between overstorey pine trees and pine seedlings, signif. codes: 0 ‘\*\*\*’, 0.001 ‘\*\*’, 0.01 ‘\*’, 0.1 ‘n.s.’).

Site	Microsite Type Parameter	Estimate	Std. Error	CI95.lo	CI95.hi	Ztest	Zval
KATa	m1	−1.0416456	0.05252133	−1.1445855	−0.9387056	***	−19.832808
	m2	0.0863855	0.11610683	−0.2441196	0.4168907	***	9.715459
	m6	−0.0725547	0.15514918	−0.4795814	0.3344714	***	6.246188
	markX1xX2	−0.6660055	0.04577624	−0.7557253	−0.5762857	***	−14.549154
KATb	m1	−1.2918200	0.07544377	−1.4396871	−1.1439530	***	−17.122951
	m2	0.1799492	0.09434293	−0.1528831	0.5127250	***	15.600207
	m3	−0.4782191	0.11767162	−0.8567093	−0.0997110	***	6.914241
	markX1xX2	−0.1748097	0.00615304	−0.1868695	−0.1627500	***	−28.410310
WEB	m1	0.0842216	0.02998521	0.0254516	0.1429915	**	2.808770
	m2	−0.3185780	0.14891511	−0.6692162	0.0320601	**	−2.704894
	m3	−0.9400014	0.55854394	−2.0934977	0.2134942	n.s.	−1.833738
	m6	−2.3639542	0.57812840	−3.5558351	−1.1726635	***	−4.234658
	markX1xX2	−0.3952673	0.01691281	−0.4284158	−0.3621188	***	−1.833738
NEF	m1	−0.6336548	0.04722066	−0.7262056	−0.5411040	***	−13.419017
	m2	0.7599928	0.07192198	0.5264775	0.9935081	***	19.377215
	m3	−0.1041160	0.14754053	−0.4858410	0.2776089	***	3.589107
	markX1xX2	−0.5588286	0.02523363	−0.5093716	−0.5093716	***	−22.146181
TEM	m1	1.0929196	0.01859953	1.0564652	1.1293740	***	58.760602
	m2	1.3021970	0.05467421	1.1585831	1.4458109	***	3.827718
	m3	0.9125870	0.07405674	0.7309841	1.0941900	*	−2.435060
	markX1xX2	−0.1713702	0.00277762	−0.1768142	−0.1659262	***	−61.696738

Table 9. Cont.

Site	Microsite Type Parameter	Estimate	Std. Error	CI95.lo	CI95.hi	Ztest	Zval
BRE	m1	1.5765652	0.04217726	1.4938993	1.6592311	***	37.379510
	m2	2.3397087	0.05890207	2.1415969	2.5378205	***	12.956141
	m3	1.9592090	0.07960589	1.7205184	2.1978996	***	4.806727
	m4	2.0476753	0.06157934	1.8443161	2.2510345	***	7.650457
	m5	1.7668650	0.12001474	1.4489745	2.0847554	n.s.	1.585637
	markX1xX2	−0.0662259	0.00246044	−0.0710482	−0.0614035	***	−26.916310
DAN	m4	3.3911820	0.02022783	3.3515360	3.4308280	***	167.64930
	m5	2.6463600	0.02164218	2.6039420	2.6887780	***	122.27790
	markX1xX2	-	-	-	-	-	-

The MSH calculations produced negative parameters for the interactions between overstorey trees and seedling densities for all sites except DAN (Table 9). All were highly significant ( $p$ -value = 0.000). However, the parameters of interaction between overstorey pine trees and seedlings were of varying intensity. With the exception of the site KATb, the observation that the higher the seedling intensity of microsite type with undisturbed soil conditions (m1), the lower the interaction parameter, holds. Thus, when favourable ground conditions prevail, indicated by high seedling densities, the additional effect of the overstorey trees on seedling density is low. There was no interaction effect of microsite and overstorey trees on the high seedling density on the strongly scarified site DAN.

#### 4. Discussion

##### 4.1. Pine Seedling Density and Growth Affected by Overstorey Trees and Microsites

The silvicultural management of Scots pine stands is based on the combined use of overstorey trees as shelter trees and mature pine trees as seed trees. A higher seed input can be assumed in pine stands with higher basal areas [14,28], but at the same time, the number of cones is strongly related to the crown surface area [66]. This means that continuous crown maintenance is necessary to support seed production. The number of mature trees per hectare must be limited to ensure the free development of crowns, without intraspecific crown competition, to allow for optimal seed production. A highly significant negative relationship between stand density and the number of cones produced per tree was described for longleaf pine (*Pinus palustris* Mill.) and Aleppo pine (*Pinus halepensis* Mill.) [67,68]. A moderate 100 mature trees per hectare was declared the most effective stocking density to stimulate cone production in stone pine (*Pinus pinea* L.) [69]. Our study sites represent a wide range of densities of overstorey trees and, consequently, basal areas. The sites KATa and WEB possessed few overstorey trees (<50 per hectare) so that seedlings could clearly be assigned to a seed tree. The remaining sites were characterised by denser stand conditions (>50 trees per hectare), more typical of shelterwood systems. Overstorey trees act as shelter trees, representative of the highest hierarchical level of vertical forest structures. Shelter or overstorey trees affect small-scale environmental conditions like the climate of the stand interior or the availability of light and water, which is relevant for the germination and growth of seedlings within the lower hierarchical levels [14]. These conditions are also crucial for the species constellations, and their seedling abundance, on the ground and in the midst of different ground cover types [12,70,71]. Experimental studies have shown the rapid and nearly complete recolonisation of the ground four years after soil preparation at clear-felled sites compared to 50% recolonisation of the ground where shelterwood cuts retain 200 stems per hectare [14]. The combination of seed-producing trees and shelter effects are the basic principles of seed tree and shelterwood cuts, the silvicultural systems are mainly used to establish pine seedlings naturally [40,46,72,73]. Clear differentiation between both systems based on the number of seed trees per hectare is not possible because the transition between both systems is usually fluid and adapted to the site conditions [18], but each system follows different silvicultural procedures and management targets. The

seed tree system aims to maximise the use of the overstorey trees, followed by very short regeneration periods producing adequate seedling densities [35]. The fast removal of seed trees is recommended, especially on dryer sites, because the seedling growth may decline quickly as a result of competition pressure [18]. There are greater risks inherent in the seed tree system should natural regeneration fail due to extremes of weather, a lack of fructification, or the rapid establishment of expansive ground vegetation [6,74]. The silvicultural options available to control the growth of seedlings by manipulating the remaining seed trees are also low. In contrast, the shelterwood system guarantees a continuous input of sufficient seeds under favourable micro-climate conditions, while depressing the expansion of competing ground vegetation [14,28]. The densities of between 5900 and 199,000 pine seedlings observed per hectare indicated that, on the basis of the regional silvicultural targets for natural pine seedling regeneration densities, regeneration was successful on all study sites [46]. However, the fact that the age of the seedlings differed between the sites must be taken into account. On the sites BRE and DAN especially, with the youngest pine seedlings, significant mortality rates can still be expected. Taking all of our study sites and the observed seedling ages into account, the pine seedling densities on the microsite type representative of stand conditions without soil scarification (m1) showed no significant relationship between basal area and seedling density. The seedling densities in these areas were significantly influenced by the specific ground cover and microsite types [36,46,71]. Typically, the quantity of pine litter increases with increasing stand density or basal area [75], but overall, the pine seedling densities observed were only slightly related to increasing proportions of litter or moss [21,28]. An increase in the proportions of both *Vaccinium* species was significantly negatively correlated to pine seedling density and hampered the early process of pine seedling establishment [21,76–78]. This accords with the findings of previous studies that have mentioned the great importance of soil scarification on sites dominated by *Vaccinium* species [23]. Apart from the above-ground competition, the main part of the root zone of *Vaccinium myrtillus* extends to 30 cm [42], creating considerable below-ground competition. However, interactions between seedling density and the microsite type without soil scarification (m1), dominated by different ground covers, become more explicit when the age of seedlings is taken into account. It could be shown that older seedlings grow in ground cover types dominated by pine litter and *Vaccinium* species significantly more often than younger seedlings. It should be noted that seedlings of higher ages directly shape their surroundings, whereas seedlings with an age of only 1 or 2 years are representative of the current ground cover and microsite conditions [79]. Hence, these small-scale conditions can be interpreted as safe sites [80–82]. Mosses offer advantageous germination and growth conditions but only where there is sufficient precipitation and the shelter effect reduces drying [45].

The coefficients of variation produced by the analyses of the seedling ages, lower on the sites managed employing the seed tree system (KATa and WEB), highlight the theoretical approaches underlying both silvicultural systems. The variation in seedling ages is much higher on the study sites with higher basal areas, the result of longer regeneration periods with the participation of several seed years. Correspondingly, the risks are lower in terms of management [23]. The higher pool of seed trees can be seen as favourable in terms of the genetic diversity and the associated resistance and resilience of seedlings to abiotic and biotic influences [83,84]. By exploiting different seed years, the shelterwood system increases the probability of a more structured natural pine regeneration, which is also shown by the higher variations in the growth parameters. It is well known, however, that it is difficult to establish highly structured and uneven-aged pine regeneration under mono-layered pure pine forests by means solely of the manipulation of the overstorey trees [5]. Continuous, highly structured and uneven-aged forests are not typical of pure pine stands, being a light-demanding, pioneer tree species [8,85]. The development of well-structured pine stands depends on natural disturbances, often combined with soil scarification occurring as a result of fire or windthrow [21,81,86]. Well-known historical analyses of near-natural forest management concepts for pine forests in Germany demonstrated

that the increased variation in the structure of pine regeneration achieved solely through periodic overstorey treatment necessitates elaborate, sophisticated management [87,88]. Another study demonstrated that the creation of gaps leads to different seedling densities and modified ground cover conditions [21]. The highest seedling densities were observed within gaps with diameters of 20 m, proving more suitable than gaps with diameters of 40 m and 80 m. It was demonstrated in four different Scots pine forest stands that selection systems should mimic natural disturbances and be focused on a continuous ingrowth of smaller trees [4]. Without soil scarification, heavy reductions of the basal area followed by periods of several decades without thinning are considered beneficial for the creation of multi-layered pine forests.

Our results clearly show the direct effects of overstorey density on pine seedling growth. The findings of the age-dependent analyses demonstrated the strongly reduced height growth of seedlings sheltered by stands with higher basal areas. The strength of the effects on seedling growth was also found to depend on the duration of seedling development under specific stand densities. Although these factors have been identified as being the most important for height growth in pine seedlings, it could be shown that soil scarification increases height growth by 1 m after 10 years of development [18]. A further intensification of soil scarification has been found to lead to reduced seedling height growth [89]. The shelter-dependent differences in total regeneration height can reach 2–3 m after 10 years [36,90–92]. A reduction in the annual height growth in pine seedlings has also been documented in the northeast German lowlands [71]. The authors described a mean reduction in annual shoot lengths in seedlings of 50 cm along a basal area gradient of old pine forests between 0 and 35 m<sup>2</sup> per hectare. In the first years of development, the seedlings on our study sites exhibited comparable growth parameters, but from an age of 5 years, the influence of the basal area of the overstorey trees could be proven to be significant. Although recent studies have documented changes to the growth of Scots pine strongly linked to climate and site [93], an early culmination in height increment between the ages of 15 and 30 years is typical in the study region and limits any extension of the regeneration timeframe [94]. A strong depression in pine seedling growth was also described for sites in the Netherlands [76], leading to the conclusion that thinning is necessary approximately 5 years after successful seedling establishment in order to avoid growth losses and to maintain vitality. Growth indices like slenderness and live crown radius can also be used to recognise vitality and stability problems in pine seedlings, helping to identify whether the period of high shelter might be proving too long for light-demanding tree species [4,56].

#### 4.2. Supporting Spatially Heterogeneous Pine Seedling Patterns

In addition to total pine seedling densities, the spatial distribution of seedlings is also of great importance for close-to-nature silvicultural concepts aiming for higher structural diversity and keeping open the option to integrate other tree species [95]. From studies of natural forests, it is known that regeneration success and the spatial patterns of pine seedlings are strongly dependent on natural disturbances and an abundant seedlinebreak fall [23], strongly related to the position of adult trees and the prevailing weather conditions [85,96,97]. Those disturbances that create canopy gaps tend to damage unfavourable ground vegetation types like grasses and shrubs (see *Vaccinium* species above) and generate surfaces dominated by mineral soil, conditions beneficial for the early stages of pine regeneration [21,45]. Under natural conditions, the creation and distribution of these disturbed areas are initiated by random abiotic and biotic processes [8]. Silvicultural management is oriented towards mimicking these processes by creating patches of exposed mineral soil using different technical methods like cultivators or light ploughs with high manoeuvrability pulled by horses. Especially the latter is more in line with the natural and more irregular soil disturbances that often occur, e.g., due to wild boars or windthrows. In principle, light ploughs are used, which do not interfere or do not interfere deeply with the mineral soil. Thus, only the humus layer is removed. These ploughs often have two

shares and may have been developed by the company itself, e.g., double mould-board forest ploughs. Studies of natural pine regeneration under pine shelters have described different distribution patterns (clumped, regular, or irregular) for pine saplings absent prior soil scarification [5], but unfortunately, specific information about microsites or the spatial patterns of overstorey trees is lacking. Particularly high seedling densities were observed on the study sites BRE and DAN, where soil scarification was practised approximately 3 years prior to data collection, using a cultivator and a plough, respectively. On both sites, the comparatively young age of the pine seedlings, about 2 years, was a direct result of the soil scarification treatments [23]. Comparable seedling densities of more than 100,000 pine seedlings per hectare were observed on fully ploughed forest areas [36,76,98]. Both soil scarification techniques helped to establish high seedling densities, particularly in the first 2 years after scarification. The seedling densities and their distributions differed strongly, however, in accordance with the spatial distribution of the scarified surfaces. The use of a cultivator created small aggregates, and there were additional differences in seedling densities between the resultant pits and mounds. This served to increase the spatial heterogeneity ( $RCE$  0.3) within the regeneration layer of the pine stands [47,76]. The complete scarification of the site DAN led to less clumped spatial patterns ( $RCE$  0.7) of pine seedlings and a more homogeneous age structure. The gentler soil scarification of the site TEM, achieved using a horse-drawn plough, occurred sometime earlier and was no longer visible amongst the microsite types, but the high seedling densities (29,000 seedlings per hectare) on m1 proved a continuous success of regeneration. The seedling densities on hollows (BRE) and furrows (DAN) were higher than on mounds, in particular on the site BRE, with small patches prepared using a cultivator. An explanation is provided by the higher soil moisture in these hollows and furrows, combined with the immediate soil contact achieved by the radicle [14,45]. These conditions form safe sites favourable for seed germination and the fast development of roots, which can increase the probability of survival [28,81,99].

Skid trails lead to strongly aggregated and dense patches of seedlings (m2 and m3), but with no relevance for the future regeneration success of the forest stands. The low mean ages of the pine seedlings (1.5 to 2.0 years) on the scarified sites BRE and DAN only allowed for a provisional assessment of the success of regeneration, because typically the mortality rates can reach up to 90% during the early stages of pine seedling development, mostly influenced by factors like drought or the competition exerted by expansive ground vegetation [45,49,100]. Successful rapid and dense regeneration is typically characterised by a few age classes [23].

Finally, the spatial effects of overstorey trees were assessed in combination with different microsite conditions by using different interaction radii analyses. Our findings, achieved using multitype Strauss hard-core process (MSH), show a negative interaction between overstorey trees and pine seedling densities. Countering to some extent the positive sheltering effect of overstorey trees, in particular during long-term extreme climate events, the superior root competition of overstorey pine trees impacts regeneration [39,40,70]. Mycorrhiza associated with overstorey trees have also been shown to impact the development of *Pinus radiata* D. Don seedlings [101]. The spatial effect zone of adult pine trees, indicated by the crown projection on the ground, either prevents regeneration entirely or reduces the density and the growth of seedlings [70,102], because of the competition for water and nutrients. The dominance of mature Scots pine trees within 3.5 m to 5 m of the surrounding upper soil layer area was also discussed by Valkonen [40] resulting in lower seedling densities. A drastic decrease in pine seedling height growth was observed at distances of between 0.5 and 1.2 m from adult Scots pine trees [103]. Such effect zones in the surrounding of adult pine trees create heterogenous spatial distributions of pine seedlings. The calculated interaction parameters of the MSH process revealed stronger effects on study sites with low numbers of overstorey trees. This effect is low on sites where the overstorey trees cast dense shelter. On the sites with intensive soil scarification and young seedlings (site DAN), the root zone effect is reduced or fully negated due to the seedlings' shallow rooting depth.

## 5. Conclusions

The findings of the study demonstrate that both silvicultural systems—seed tree and shelterwood cuts—are fundamentally suitable to initiate sufficiently dense natural regeneration (>5000 seedlings per hectare) in Scots pine. The regeneration densities could be further increased by adopting soil scarification methods. However, the soil scarification method chosen has a significant influence on the spatial distribution of pine seedlings and on future intraspecific competition. On sites without soil scarification, the species composition and ground vegetation patterns, and the microsites as a whole, determine the localised success of seedling establishment. *Vaccinium* species severely inhibit the growth of pine in the establishment phase. The number of overstorey stems has little impact on the absolute regeneration density, but a significant effect on the growth of seedlings. Higher stem numbers (>200 stems per hectare) guarantee high regeneration density initially but lead to significant growth and vitality losses after a period of about 5 years if the shelter is maintained. The spatial interaction of overstorey trees and microsites had a significant negative effect on seedling density on all study sites. The spatial heterogeneity of the microsites and the overstorey trees should be given greater consideration in subsequent silvicultural treatments to produce age- and growth-related structures in the regeneration and to allow for small-scale regeneration of additional tree species.

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