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Effects of Site Preparation Methods on the Establishment and Natural-Regeneration Traits of Scots Pines (*Pinus sylvestris* L.) in Northeastern Poland

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Abstract: While some tree species can regenerate naturally without mechanical site preparation (MSP), Scots pine has been shown to benefit from this process. We compared three methods: using a double-mouldboard forest plough (FP), an active single-disc plough (AP), and a forest mill (FM), as well as a no-MSP control, in terms of growth, survival and density of occurrence of pines during the first 4 years of natural regeneration. Moisture conditions were expressed via calculated de Martonne aridity indices, while the microhabitats generated via different MSP methods were further characterised by the total contents of N and C, and the C/N ratio, P_2O_5, and base cations, as well as bulk density and actual moisture. The trials showed inferior regeneration without MSP in terms of the density and cover of young pines. Any of the studied treatments influenced survival, though the best growth was achieved by seedlings using the FP and AP methods, while the best density and evenness results were obtained using AP. The factors most influencing regeneration features were high precipitation during the first growing season after sowing and reduced competition with other vegetation in the cleared area. This impact seems far more important than the capacity of different MSPs to produce differentiation in soil microhabitats in terms of nutrient status or bulk density.

Keywords: soil scarification; self-sowing; seedling density; seedling growth; seedling survival; clear-cut

1. Introduction

Scots pine (*Pinus sylvestris* L.) is one of the most important tree species in Europe and covers about 12×10^6 ha of forest land [1]. In Polish forests, it constitutes 58.2% of the area and 60.8% of the volume [2]. However, while Polish forestry mainly applies clear-cutting followed by the planting of 1-year-old seedlings to regenerate Scots pine stands [3], is increasingly typical for pines to regenerate via self-sowing. In 2016, this method was applied to over 13.6% of the entire area assigned for regeneration [2]. The approach can be justified by the frequent occurrence of masting years among pines, the prevalence of nutrient-poor coniferous forest site-types in Poland (in more fertile site types, natural regeneration of Scots pine usually failure due to competition with herbaceous vegetation), and a conviction that it is more environmentally friendly [4,5].

The level of natural regeneration achieved among pines is conditioned by aspects of weather such as precipitation and temperature [6–8], as well as by soil-surface properties, above all the thickness of litter and humus layers and their moisture levels. A high content of organic matter ensures rapid desiccation of these layers, and hence widely variable humidity [9]. Furthermore, where the soil is not scarified, the thickness of the aforementioned layers often denies or delays contact between the seedling roots and mineral soil [10,11]. These factors leave germination and seedling survival highly dependent on precipitation amounts and intensities [12]. It is for such reasons that mechanical site preparation (MSP) is recommended, so that optimal conditions for germination and growth can be achieved [3,6,13]. Other benefits of MSP include limiting competition for light, water and nutrients between seedlings and herbaceous plants in a clear-cut area [14]. This is of particular importance in the first and usually second year of seedlings life, while the small size of seedlings and high pressure of competition from herbaceous vegetation may finally lead to natural regeneration failure. Forest-floor plants may obstruct and delay germination, as well as deploy allelopathy to confine seedling growth [15,16]. MSP also reduces potential damage by the pine weevil (*Hylobius abietis* L.), which is known to avoid mineral soil, because it has difficulty moving across it and because of the increased risk of predation that entails [17]. Small mammals and birds feeding on seeds are also inhibited, because rodents dislike climbing on ridges, given the lack of vegetation and elevated position [18].

A negative impact of MSP may be leaching of mineral components and consequent impoverishment of the soil [19–21]. Most site preparation methods can result in soil erosion if not carefully implemented and adapted to specific site characteristics and climate [13,22].

MSP modifies physical conditions of the soil, such as water content, aeration, temperature and bulk density, as well as chemical properties such as organic matter content, availability of nutrients and soil reaction [23–26]. Thus, the modification of soil physical and chemical properties, caused by the MSP, directly effects the seed germination and survival rate of seedlings, and can accelerate their growth under the given climatic conditions, forest site-type and species undergoing regeneration [13,25,27–29].

Basic MSP methods include removing forest floor to expose mineral soil, inverting forest floor and mineral soil, elevating mineral soil, and mixing forest floor with mineral soil [25,30]. MSP utilises various tools and machines that differ in the degree to which the soil is disturbed, as measured in terms of area and depth [31,32]. According to many comparative studies, more-intensive scarification methods (measured by the area and depth of the disturbed soil) usually encourage more seedlings initially, and better subsequent growth and survival [33–36]. However, comparing the different MSP methods over longer time scales, tree growth is poorest when full removal to sides of forest floor (to expose mineral soil) was applied, and best in cases where the forest floor and mineral soil were mixed [25,37].

In Poland, use of the traditional double-mouldboard forest plough (FP) has long represented the most widespread means of preparing clear-cut sites. The FP treatment has gained use in both artificial regeneration (planting) and natural regeneration, and forestry practitioners are typically convinced that it is the best MSP method. This probably reflects the fact that FP in Polish climatic conditions (with frequent spring droughts and annual precipitation totals below 550 mm in many places) ensure the best conditions for germination, while also providing effective elimination of herbaceous vegetation over the clear-cut area, limiting competition with one-year-old pine seedlings. Thus, it ensures successful natural regeneration of pines, especially where seedling density and the evenness of cover are concerned (for more details see also [38]). However, as the FP method greatly modifies the soil structure, affecting nearly the whole area of a clear-cut [32], today's forestry increasingly seeks more environmentally friendly solutions. Although the less-intense soil preparation methods such as an active plough (AP) or a forest mill (FM) are applied increasingly in Poland, their impact on the performance and basic growth characteristics in case of natural regeneration remain poorly studied and understood.

Thus, the work detailed here aimed to compare the influence of the FP, AP and FM methods of MSP with a no-MSP approach, in relation to the growth, survival and density of Scots pine seedlings during the first 4 years of natural regeneration. We wanted to indicate if the MSP is necessary, and whether it creates conditions for establishing the best natural pine regeneration in taking into consideration local climatic conditions.

We assumed that natural regeneration with the most favourable parameters would be achieved by using the double-mouldboard forest plough (FP). This regeneration was therefore expected to produce the highest density and evenness of cover, as well as comparable or at worst slightly poorer growth than with other methods.

2. Materials and Methods

2.1. Study Area

Field research was conducted in Poland's Spychowo Forest District, ca. 150 km north-east of Warsaw (53°36′ N, 21°20′ E; WGS 84). The soil in the study area is classified as podsolic, formed on loose sands with typical more humus. Specifically, trials were run in a clear-cut area 400 m long with a width of 50 m in the narrower half and 64 in the wider. Before felling, the stand had comprised 129-year-old Scots pine trees (*P. sylvestris*) (with a stand volume of 260 m^3 ha^{-1}, a stand density of 390 stems/ha, an average tree height of 24.5 m, and average tree diameter at breast height (dbh) of 34 cm). To the east, the felled area bordered a plantation with pines regenerating naturally, with an admixture of spruce. On the other three sides it was surrounded by pine stands of various ages (79 years to the south, 102 years to the west and 56 years to the north-west). The herb layer was dominated by *Dicranum polysetum* Sw., *D. scoparium* (L.) Hedw., *Vaccinium myrtillus* L., *V. vitis-idaea* L., *Calluna vulgaris* (L.) Hull, *Luzula pilosa* (L.) Willd, *Festuca ovina* L. and *Lycopodium annotinum* L. The plant community was classified as *Peucedano-Pinetum typicum* Mat. [39]—i.e., the most nutrient-poor site type, accounting for 20.9% of Poland's forest [2]. It is mainly in this habitat that natural regeneration of Scots pine proves possible, as in more fertile site types, seedlings are outcompeted by herbs.

Prior to site preparation, the yield of pine cones was studied. All cones collected from five cut trees were counted. In the stand on the windward side there was an average total of 360 cones per tree, what may be described as an average yield. Soil was prepared during December 2013, and seeds were sown during the spring of the next year. Seeds were derived from the surrounding stands or from seed trees remaining in the clear-cut area at a density of 20 per ha. Prior to sowing, the site was fenced to limit damage caused by game animals.

2.2. Weather Conditions

Data on monthly precipitation and mean air temperature during the experimental period (2014–2017) were collected from the Spychowo Forest District weather station ca. 10 km from the study site. To better illustrate moisture conditions, we calculated the de Martonne aridity index (AI) [40] for each month of 2014–2017, using the following formula:

$$AI = 12P/(T + 10) \quad (1)$$

where P is the monthly precipitation (mm) and T monthly mean air temperature (°C). According to the World Meteorological Organisation [41], the AI indicates the months in which irrigation is necessary, generally when AI < 20 (Table 1).

Table 1. Monthly average air temperature (°C), monthly precipitation (mm) and de Martonne aridity index during 2014–2017, at the Spychowo Forest District weather station.

Month	Temperature (°C)				Precipitation (mm)				Aridity Index			
	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
January	−4.3	−0.5	−5.2	−0.6	57.4	62.6	39.8	33.6	119.74	78.99	98.42	42.85
February	−0.7	0.7	1.8	0.4	30.9	51.9	146.4	68.0	39.78	66.69	148.87	78.60
March	4.4	4.0	2.1	4.2	5.1	94.5	30.0	57.1	4.21	81.24	29.82	48.31
April	8.2	6.6	7.6	6.8	60.3	69.1	62.3	98.3	39.72	49.96	42.57	70.23
May	12.8	11.5	13.0	13.5	42.9	60.7	82.6	31.1	22.61	33.91	43.18	15.87
June	14.4	15.4	17.5	17.9	65.9	37.6	33.4	28.6	32.49	17.76	14.61	12.32
July	19.6	17.7	18.0	18.2	180.2	99.4	81.3	166.2	73.10	43.01	34.90	70.83
August	17.0	19.8	16.8	18.6	126.8	6.9	123.8	93.7	56.38	2.76	55.44	39.30
September	13.5	14.1	13.9	14.1	43.7	77.2	18.0	228.3	22.31	38.46	9.05	113.77
October	8.0	6.1	6.6	8.8	22.8	12.5	166.2	171.0	15.18	9.31	119.89	109.19
November	2.5	4.1	2.4	4.3	9.5	138.1	103.1	55.0	9.06	117.51	99.80	46.06
December	−1.2	3.2	1.2	1.7	33.2	115.7	94.8	106.8	45.10	105.30	101.86	109.09

2.3. Treatments

The experiment consisted of four treatments distinguished on the basis of the MSP method (FP, AP, FM and the no-MSP control). Each experimental treatment was represented by four replicates. The cleared area was therefore divided into four even parts (blocks of sides 100 m). Each block was then subdivided into four plots (of 50 m × 25 m or 50 m × 32 m size), with each plot then used to test different types of MSP (Figure 1).

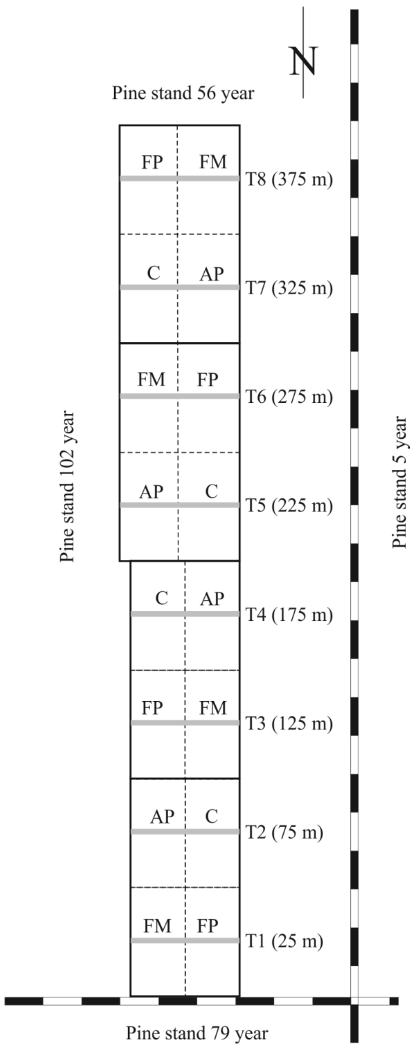

Figure 1. Experimental design (FP—forest plough; AP—active plough; FM—forest mill; C—control, no-MSP; T—transects).

MSP was performed using either an LPz OTL double mould-board forest plough (FP), a P1T active single-disc plough (AP), or an FL forest mill (FM) (manufacturer: Ośrodek Techniki Leśnej, Jarocin, Poland, http://www.otljarocin.lasy.gov.pl/preparation-of-soil-and-afforestation).

The furrows made by the FP are rectangular, 70 cm in width and 5–10 cm deep. Leaf litter and the humus layer are cut and placed as ridges on both sides of the furrow, in which mineral soil lies exposed. Furrows account for 50% of the surface area, while the other 50% is ridges. Using an AP, the rotating disc forms parabolic furrows, 40 cm in width and up to 10 cm deep. A partial mixing of leaf litter and some of the humus occurs, as these are piled on ridges. A furrow-bottom is scarified and covered with a mixture of humus and mineral soil. In this MSP method, furrows account for 40% of the surface area, ridges for 40%, and undisturbed soil the remaining 20%. Using an FM, the working part is a horizontal cylinder with cutting blades revolving at a rate of 1000 rpm. This achieves a crushing and mixing of forest vegetation, leaf litter, humus and mineral soil to a depth of 30 cm in strips 40 cm in width (27% of the surface area). The undisturbed strips between are 110 cm in width (73% of the surface area). For all of the MSP methods, the distance between the centres of the neighbouring furrows or strips was 1.5 m [32].

2.4. Measurements

Pines were measured along 1m-wide permanent transects marked in the field. There were eight such transects located 50 m apart. Each extended across the whole width of the clear-cut area, passing through the centres of the plots of different types of MSP (Figure 1). The overall lengths of transects receiving the different treatments were: FP—115 m, AP—114 m, FM—115 m, C—106 m. Measurements were made during the autumn after the first, second, third and fourth years of growth of the young pines. On each occasion, the heights of all pines along the transects were measured, with positions denoted by the distance in m along the transect. By the time the third year had elapsed, it was no longer possible to distinguish ridge, furrow, strip or non-strip microhabitats, as differences between the strip and non-strip areas in the FM variant had become indistinguishable; as had differences in the height between the ridges and furrows of the AP. Additionally, herbaceous vegetation had become well-established.

2.5. Soil Analysis

Soil analysis was conducted at the Forest Research Institute's Independent Laboratory for the Chemistry of the Forest Environment (PCA accreditation No. AB 740). Soil was sampled in late October of the first year of sowing. Sampling at the level of each MSP plot (i.e., the treatment in a block) was conducted, with four 112.3-cm^3 cylindrical samples (taken using a Kopecki cylinder, height—55 mm, inner diameter—51 mm) collected from each, as well as four combined samples (taken using a shovel, each of approximately 0.5 kg of soil) involving two samples each from the ridges and furrows under the FP and AP regimes, as well as two strip and non-strip samples each for the FM. The no-MSP plots were sampled by reference to two cylindrical samples and two combined samples. Altogether, 56 cylindrical samples and 56 combined samples were collected. Soil determinations related to total N and total C were obtained using high-temperature combustion and thermal conductivity detector (TCD) detection (N—PN-ISO 13878:2002, C—PN-ISO 10694:2002); P_2O_5 using the Egner–Riehm method (PB-20 ed. 2 dated 1 January 2010); exchangeable contents of the cations Ca^{2+}, Mg^{2+}, K^+ and Na^+ via ammonium acetate extraction at a pH of 7.0 using the inductively coupled plasma (ICP) method (PB-05 ed. 2, dated 1 January 2010), and bulk density and actual moisture by means of weighing.

2.6. Statistical Analysis

The mean values for the different response variables for each block and treatment combinations were calculated across each sample plot (1-m quadrats) prior to the analyses. Percentage survival rates were subject to Bliss (arcsine) transformation. For these variables (seedling height, density and survival rate), the influence of MSP was assessed using a linear mixed model for repeated measures observations as follows:

$$Y_{ijk} = \mu + \alpha_i + \pi_{k(i)} + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \quad (2)$$

where Y_{ijk} is the value of the analysed dependent variable in year i, treatment j and block k; μ is the overall mean; α_i is a fixed year effect (i = 1–4); $\pi_{k(i)}$ denotes random effects of block nested within year (k = 1–4); β_j is a fixed treatment effect with (j = 1–4); $\alpha\beta_{ij}$ is a fixed interaction effect between year and treatment and e_{ijk} is an error. For the proposed linear mixed model we assumed first-order autoregressive (AR(1)) variance-covariance structure for e_{ijk} effect. The significances of fixed effects were tested for used the Wald F test. For heights and survival rates in the proposed linear mixed model we added densities of occurrence as a covariate variable.

Statistical analyses of soil features were completed using the general linear model as follows:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \quad (3)$$

where Y_{ij} is the total N and total C contents, the contents of exchangeable Ca^{2+}, Mg^{2+}, K^+ and Na^+, bulk density and actual moisture; μ is the overall mean; α_i is the block effect (i = 1–4); β_j is a fixed treatment effect (MSP microsites) with (j = 1–7) and ε_{ij} is the experimental error. Differences among the MSP methods and in terms of soil features were analysed using Tukey's test (α = 0.05).

For individual MSP methods (in %) we assessed the distribution of 1m^2 plot frequencies in classes of seedling density designated 0—'zero plots' (with no seedlings); 1—1–5 seedlings; 2—6–10 seedlings; and 3—more than 10 seedlings. To test for significant differences in proportions of density classes between mechanical site preparation methods we used the chi-square test.

For the statistical analysis we used the R 3.2.5 software package (The R Foundation for Statistical Computing, Vienna, Austria). The applied linear mixed model was fitted using ASReml 3.0 (VSN International Ltd, Hemel Hempstead, United Kingdom), as implemented in the R software package ASReml-R (VSN International Ltd, Hemel Hempstead, United Kingdom).

3. Results

Over the first three years, the growth of seedlings expressed in terms of height did not differ significantly from one treatment to another. In contrast, after the fourth season, pines growing in soils prepared using the FP method had reached a similar height to those with the AP treatment, with these now being significantly taller than FM or no-MSP trees (Figure 2, Table 2).

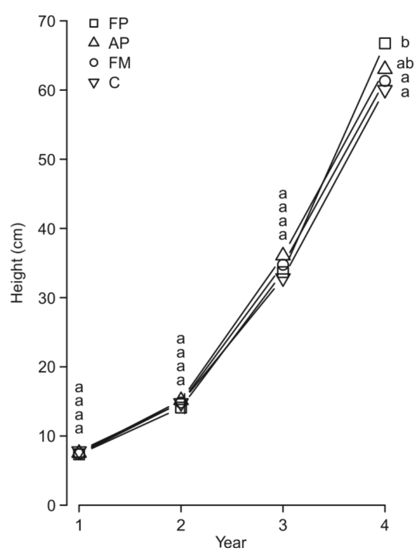

Figure 2. Mean height (cm) of Scots pine seedlings in relation to the three mechanical site preparation methods. Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$.

Table 2. Results with the linear mixed model describing the statistical significance of the tested fixed effect of mechanical site preparation (MSP) methods, seeding age and the interaction between these effects on height, density and survival of Scots pine seedlings during four growing seasons (* indicate differences significant at $p \leq 0.05$, *** indicate differences significant at $p \leq 0.001$).

Variable	Source of Variation	Wald F Statistic	Degree of Freedom	*p* Value
Seedling height	Seedling density	4.1049	1	0.04276 *
	MSP method (M)	3.0034	3	0.3911
	Seedling age (A)	4132.959	3	<0.0001 ***
	M × A	15.2052	9	0.04545 *
Seedling density	MSP method (M)	237.867	3	<0.0001 ***
	Seedling age (A)	169.495	3	<0.0001 ***
	M × A	14.299	9	0.1121
Seedling survival	Seedling density	32.8115	1	0.0001 ***
	MSP method (M)	10.7168	3	0.01336 *
	Seedling age (A)	229.5242	2	<0.0001 ***
	M × A	2.4329	6	0.8759

After the first year of growth, the density of pine seedlings was significantly greater as a result of MSP carried out with AP (at 9.0 seedlings m^{-2}) or FM (8.8 seedlings m^{-2}), lower with FP (at 5.8 seedlings m^{-2}), a lowest of all in the no-MSP treatment (at 3.9 seedlings m^{-2}). After four years, the relationship between the effects of the four treatments appeared similar, with the highest (4.8 seedlings m^{-2}) density noted for AP-prepared soil, and the lowest (1.5 seedlings m^{-2}) where there had been no MSP (Figure 3, Table 2).

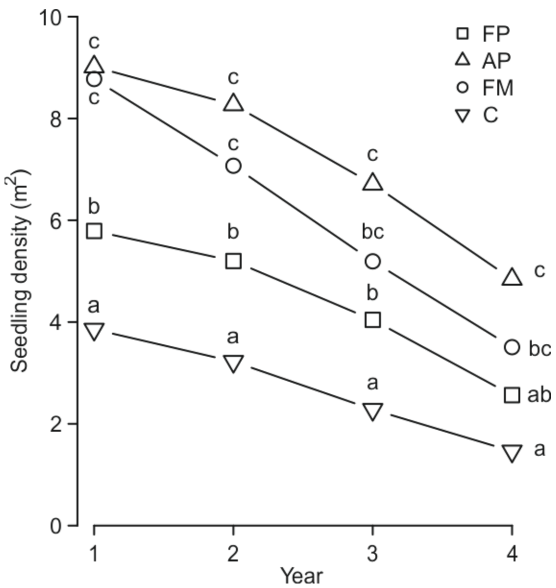

Figure 3. Average density (m^2) of Scots pine seedlings in relation to MSP methods. Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$.

After the second, third and fourth years of the experiment, no differences in survival among pines were to be noted in relations to treatment. After four years, survival rates could be ordered as follows: FP—59.2%, AP—58.5%, FM—57.0% and C—57.0% (Figure 4, Table 2).

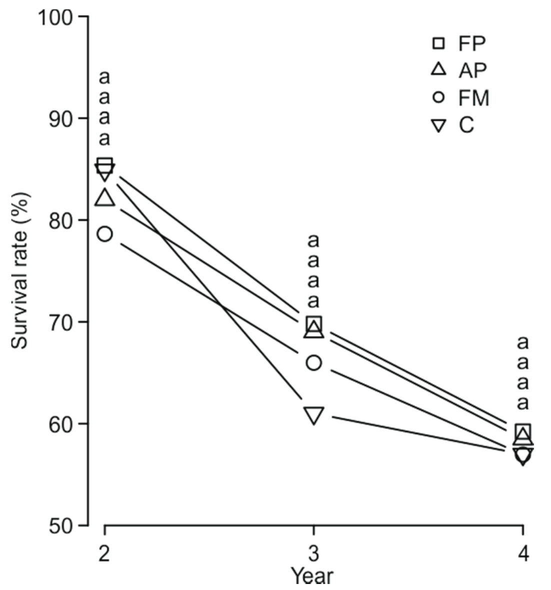

Figure 4. Survival rates of Scots pine seedlings after the second, third and fourth years in relation to MSP methods. Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$.

At the level of the individual 1 m^2 plots, the most favourable density of pines was achieved using AP. Just 11.4% of the plots receiving this treatment supported no pines after four years during the trials. In contrast, 53.8% of the no-MSP plots supported no pines. In this regard, FM was also a more favourable option than FP (seedling density classes 0, 1, 2, 3 $p < 0.0001$) (Figure 5).

N contents in the ridges of the two types were significantly higher than in the no-MSP soil (FP at 1.64 g kg^{-1} and AP at 2.23 g kg^{-1} versus no-MSP at 0.96 g kg^{-1}), while they were significantly lower in the FP furrows (at 0.46 g kg^{-1}). In both treatments FP and AP N contents in the ridges were significantly higher than in the furrows. Similar relationships applied to C, with contents in the ridge soil (FP at 31.6 g kg^{-1} and AP at 46.1 g kg^{-1}) significantly higher than that of the no-MSP (20.7 g kg^{-1}). Contents in furrows were lower (FP at 9.3 g kg^{-1} and AP at 10.9 g kg^{-1}). Both ridges (FP and AP) contained more C than the furrows corresponding to them. The cations Mg^{2+} and K^+ were more abundant in both (FP and AP) types of ridge than in the no-MSP soil. The exchangeable Ca^{2+} content was only significantly higher than that of the no-MSP approach on the ridges created using the AP method. Ca^{2+}, Mg^{2+} and K^+ contents were significantly higher in FP and AP ridges than in the furrows corresponding to them (Table 3).

In the cases of the remaining parameters, i.e., the C/N ratio and contents of P_20_5 and Na^+, the soil samples showed no statistically significant differences between the means for the different microhabitats forming with or without MSP, as well as for the different types of MSP. The bulk density of the FP ridge-soil was lower than that of the no-MSP soil, though results for actual moisture did not show any statistically significant differences. Bulk density values were significantly lower in the FP and AP ridges, than in the furrows corresponding to them. The soil of the FM strips did not differ from that outside the strip in relation to any of the parameters studied (Table 3).

Table 3. Soil characteristics (mean and standard error in parentheses and p value) in relation to the mechanical site preparation (MSP) methods and microsites. Different letters indicate significance difference according to the Tukey test, $p < 0.05$.

Feature	Forest Plough		Active Plough		Forest Mill		Without MSP	p Value
	Ridge	Furrow	Ridge	Furrow	Strip	Outside the Strip		
Total N (g kg^{-1})	1.64 (0.104)d	0.46 (0.034)a	2.23 (0.288)e	0.54 (0.042)ab	1.07 (0.081)c	0.96 (0.092)bc	0.96 (0.044)bc	<0.0001
Total C (g kg^{-1})	31.6 (1.787)c	9.3 (0.710)a	46.1 (6.603)d	10.9 (0.803)a	22.4 (1.41)b	20.2 (1.922)b	20.7 (1.009)b	<0.0001
C/N	19.4 (0.368)a	20.3 (0.710)a	20.5 (0.438)a	20.5 (0.711)a	21.0 (0.383)a	21.1 (0.553)a	21.5 (0.215)a	0.1136
P_2O_5 (mg 100 g^{-1})	6.37 (0.522)a	8.59 (0.434)b	6.75 (0.423)ab	7.92 (0.348)ab	8.27 (0.508)ab	6.99 (0.597)ab	7.05 (0.546)ab	0.0149
Ca^{2+} (mg 100 g^{-1})	11.31 (1.776)b	1.57 (0.128)a	18.25 (3.079)c	1.97 (0.328)a	6.32 (1.095)ab	5.96 (0.610)ab	5.51 (0.569)ab	<0.0001
K^{+} (mg 100 g^{-1})	5.38 (0.533)b	1.16 (0.101)a	7.32 (1.094)b	1.28 (0.087)a	2.79 (0.271)a	2.68 (0.202)a	2.50 (0.168)a	<0.0001
Mg^{2+} (mg 100 g^{-1})	1.681 (0.216)b	0.235 (0.016)a	2.757 (0.431)c	0.274 (0.031)a	0.957 (0.148)ab	0.914 (0.088)ab	0.820 (0.073)a	<0.0001
Na^{+} (mg 100 g^{-1})	0.272 (0.035)a	0.170 (0.031)a	0.242 (0.034)a	0.131 (0.046)a	0.223 (0.028)a	0.219 (0.028)a	0.145 (0.029)a	0.0564
Bd (g cm^{-3})	0.74 (0.084)a	1.36 (0.023)c	0.85 (0.111)ab	1.29 (0.036)c	0.92 (0.058)ab	1.12 (0.044)bc	1.10 (0.064)bc	<0.0001
Am (g 100 cm^{-3})	17.2 (3.366)a	12.6 (1.238)a	16.1 (2.357)a	13.7 (1.399)a	15.6 (2.394)a	19.4 (3.414)a	20.6 (3.025)a	0.3010

Bd—bulk density, Am—actual moisture.

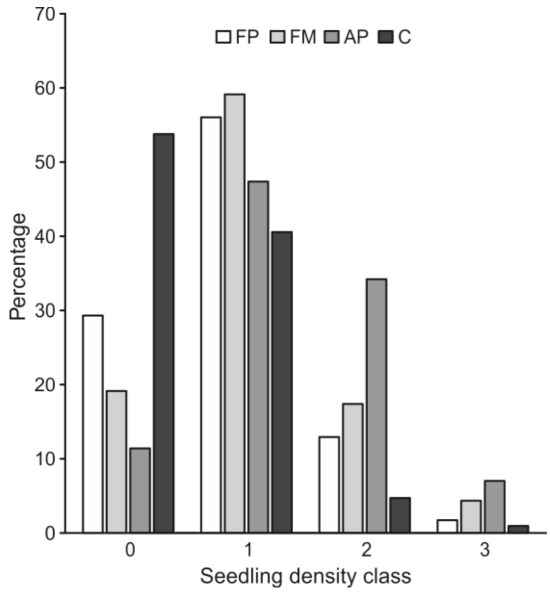

Figure 5. Breakdown of data at the level of the 1 m^2 plots (%) for Scots pine seedling density classes from four-year-old natural regeneration in relation to mechanical site preparation methods. Seedling density classes: 0—"zero plots" lacking seedlings; 1: 1–5 seedlings; 2: 6–10 seedlings; 3: more than 10 seedlings per 1 m^2.

4. Discussion

After four years of growth trials, the results for natural regeneration among Scots pines differed in relation to almost all parameters studied. In terms of density of young trees, the breakdowns by groups of 1 m^2 plots for density and seedlings height, the best regeneration was achieved using the AP method.

Achieved seedling density can be regarded as the most important aspect of natural regeneration. After 1 year, the highest value for density was the 90,000 seedlings ha^{-1} obtained using AP. The comparable figure was slightly lower for FM (at 88,000) and considerably lower for FP (58,000). However, even the latter value was well above the 39,000 seedlings ha^{-1} characterising the no-MSP plots. Nevertheless, the values obtained using FP and AP could be regarded as relatively low when compared with results from other research conducted in Polish conditions, though those noted here for FM were actually more favourable (the work by Aleksandrowicz-Trzcińska et al. [38] obtained densities of seedlings of 188,000 ha^{-1} in the case of FP, 121,000 for AP, and just 36,000 ha^{-1} for FM). However, density figures may be even higher, for example 360,000 seedlings ha^{-1} [42]. According to the instructions for assessing natural regeneration of pine in Poland, the optimal density of 1 year old seedlings is considered to be over 50,000 seedlings ha^{-1}, while in case of 4 years old more than 15,000 seedlings ha^{-1}. Four years into the experiment, the ordering of treatments in terms of density achieved was the same, i.e., AP > FM > FP > No-MSP (the respective ha^{-1} figures being 48,000; 35,000; 26,000 and 15,000). Ultimately, these data may be regarded as satisfactory from a silvicultural perspective [3].

Karlsson and Nilsson [43] considered soil scarification to be generally beneficial to species producing small, wind-dispersed seeds. However, this is not equally true of all species. The authors achieved higher densities of regenerated birch in a clear-cut area with non-scarified soil. Likewise, spruce has not been shown to benefit from soil scarification [43]. However, studies completed in European countries make it clear that soil preparation does have a favourable influence on both the density and evenness of cover of Scots pine seedlings in terms of natural regeneration [9,42,44]. Our results show that pine regeneration might be achieved without soil preparation, but only at a lower density and with greater unevenness (more than 50% of 1 m^2 plots without seedlings). In any case, seedlings mainly appear where superficial layers of soil are disturbed, particularly during harvesting and post-harvest cleaning occurring at the clear-cut site.

Most studies have shown that bare mineral soil is the optimal seedbed for the germination of forest-tree seeds [33,45,46]. In such conditions, seeds have better contact with the soil surface and better moisture conditions, given the capillary water transport to the soil surface, compared to the humus or organic horizon [12,47]. Where values for organic matter content are high, the consequence is a rapid drying out of a seedbed that is not very readily wettable. Thus, where precipitation totals are low, neither the germination of seeds nor the growth of seedlings is especially favoured [48]. As a result, it is typical for the seedling density with natural regeneration on a clear-cut area to be highest where the soil is prepared using the FP method, only slightly lower where AP is applied, and the lowest of all along the strips obtained using FM [38]. However, the results of our work do not support the hypothesis that the highest-density natural regeneration occurs where site preparation involves AP. This is most likely a reflection of local microclimatic conditions, with large amounts of precipitation and a relatively high temperature during the germination period and the first several weeks of seedling life [8].

It is considered that the minimum mean annual precipitation total allowing for natural regeneration is 550 mm/year, of which approximately 300 mm falls during the growing season [4]. Where the precipitation total is so low, the highest densities of natural regeneration are achieved with a soil prepared using FP, compared to AP or FM [38]. During the years with lower precipitation FP creates the best condition for germination due to the capillary transport of water to the soil surface, but during years with high precipitation soaking does not play a major role because seeds and seedlings mainly use water from precipitation [12,47].

During our experiment, the precipitation total during the germination period was high, with 60.3 mm falling during April and 42.9 mm during May. The respective de Martonne aridity indices were 39.72 and 22.61. In turn, the precipitation total for the April–October period inclusive was nearly 550 mm. This ensured high moisture levels, not only at the bottom of furrows with mixed mineral soil and humus in the AP variants but also in the strips created using the FM treatment, in which there is a mixing of ground-up herb-layer vegetation, humus and mineral soil that ensures moisture conditions for the germination of seeds are as suitable as those in the furrows with exposed mineral soil generated using the FP method. At the end of the growing season, the moisture of all of the microhabitats was similar, showing that the MSPs did not result in any diversification of moisture conditions.

Thermal conditions for the germination of seeds were also good, if diverse. Scots pine is able to germinate as soon as the temperature reaches 5 °C, although the optimum lies within the 20–25 °C range [49]. During April, the mean daily temperature was 8.2 °C, though there were days on which the average was less than 5 °C. Such temperatures could have resulted in better conditions for germination in soil prepared using the AP and FM methods. Mineral soil is the coldest seedbed [12]. The temperature of the soil surface along a strip prepared using the FM method might even be 2 °C higher than that of exposed mineral soil under the FP treatment [25]. Likewise, the temperature of seeds lying on the mineral soil is lower by approximately 2 °C than that of seeds lying on an organic substratum or humus [12]. Thus, the thermal conditions for the germination of seeds were probably better under the AP and FM treatments than with FP. The result might have been the higher density of the seedlings present on the soil prepared using the latter techniques, as opposed to no-MSP or FP.

In addition to the density of occurrence of seedlings, a key parameter characterising natural regeneration is the evenness of the seedling surface cover. A high proportion of zero-seedling plots most often points to considerable microhabitat differentiation across a clear-cut area [43]. Analysis of data broken down to the 1 m^2-plot level—by reference to different seedling density classes—confirms differentiated conditions for germination and for the growth of naturally regenerating pine seedlings during their first years. The most favourable circumstances were those of AP treatment, with just 11.4% of the plots supporting no seedlings, and with the greatest proportion (7%) of plots assigned to class 3 (denoting more than 10 seedlings m^{-2}).

The least favourable breakdown at the plot level was that characterising the regeneration using no MSP, as up to 53.8% of the plots lacked seedlings altogether. Our results indicate that, when based on the density of seedlings, it can be concluded that obtaining natural regeneration is possible without an MSP because after 4 years, the average density was 1.5 m^{-2} seedlings, although the lack of an even distribution of seedlings (with more than half of all plots having zero) reduces the quality of regeneration significantly. Without an MSP, the undisturbed lower layer consisted of mosses (mainly *D. polysetum* and *D. scoparium*). The field layer was composed of dwarf shrubs (*V. myrtillus*, *V. vitis-idaea*, *C. vulgaris*), grass (*F. ovina*) and other plants [39]. This vegetation creates a heterogeneous surface and is known to provide conditions that are generally too dry for germination [12]. Poor contact between the seed and intact soil, particularly where the bottom layer consists of mosses, might have been the reason for the limited germination [12]. Allelopathy may also inhibit seed germination in intact soil [15,16]. The results showing a larger number of plots without seedlings where the soil surfaces are intact were also obtained by Karlsson and Örlander [44] and Karlsson et al. [50]. Because of the high proportion of zero-seedling plots, supplementary planting was needed [3].

The rapid growth of young pines during the first years of regeneration is vital if damage resulting from game animals and late frosts is to be limited, as well as competition with other plant species, in the cleared area [31]. Naturally, the rate of growth is dependent on a series of factors, of which the most important are such features of the soil in part reflecting site preparation as nutrient status, humidity and light conditions, as well as the circumstances concerning competition with herbaceous layer plants [14,25,51]. A synergy occurs among these factors, with shortfalls or excesses in regard to any of them capable of influencing growth. Moreover, while different methods of site preparation can ensure different conditions for regeneration growth [25], their influence may be further differentiated by the features of tree species involved, as well as local conditions including habitat fertility and microclimatic conditions [13,29].

The furrows obtained using FP or AP did not differ from one another in regard to nutrient status. This despite "received wisdom" that exposed mineral soil in FP furrows has the emerging microhabitat poorest in mineral nutrients [25,48]. The more favourable solution seems to be AP, as the furrows it generates retain a humus layer ensuring better conditions for growth in the young generation [25,52]. The lack of differences in concentrations of C, N and P, as well as cations, in the furrows of either studied type may reflect the type of very shallow humus layer present in podsolic soils. Both variants involving ploughing would then basically achieve the removal of the organic and humus layers from the furrows. In contrast, the higher contents of C and N and exchangeable Ca^{2+}, Mg^{2+} and K^{+} in the soil from both types of ridge suggest that the elevation of these microhabitats results in a temperature increase [25], increasing the biological activity and accelerating the decomposition and mineralisation of organic matter [19].

Unfortunately for the aforementioned theory, our work showed more intensive processes in the furrows developed using the AP method. In this sense, our results are in line with those of Piirainen [21]. On the one hand, the increased content of macro- and micro-elements within the range of the tree roots favours growth within the young plantation; on the other hand, the mineral components are more likely to leach, leaving the habitat ultimately impoverished [19–21].

Four years of growth into the experiment, the heights of the pines obtained under the different MSP variants and in the no-MSP control were ordered FP > AP > FM > C. This coincides with the degree of intervention involved in the different MSP methods in the soil environment. While FP generates 100% disturbance of the soil surface, AP leaves 20% intact, and FM 73% [32]. The greater the degree of interference in the soil in the clear-felled area the greater the level of effectiveness and persistence of removal of vegetation competing with seedlings [35] Our results confirmed that MSP in some—or any—form is favourable for more rapid growth of young pine trees. This would in turn seem to suggest that the major influence is a curbing of competition with herbaceous vegetation in the cleared area—for light, water and nutrients [14].

The growth of pines during the first years of silviculture may also be influenced by soil bulk density [25]. However, research has shown that MSP methods can either increase or reduce this [23,25,26,53]. Our work showed that it was only in the FP ridge that the bulk density values were significantly lower than those in the no-MSP treatment. Changes in bulk density may have various causes. Archibold et al. [23] showed that the higher bulk density using an MSP reflected the use of heavy equipment. In turn, MacKenzie et al. [25] showed that a lower bulk density was characteristic for microhabitats in which organic matter content is higher. Likewise, in a study by Sewerniak and Stelter [53], the bulk density of the soils at sites prepared using FM (where organic matter content was high) was lower than that in the furrows generated using the FP method.

The differences in bulk density reported in our work are in line with these other results and are associated with different amounts of organic matter in the microhabitats that the various MSP methods generate. However, these differences only achieve significance in the case of the FP furrows. A lower bulk density would favour root development, and hence more rapid growth of seedlings or saplings, while on the other hand limiting the soaking of soil to the point where seedling growth and survival depends on the amount of precipitation [26].

In any case, our experiment's relatively minor differences in bulk density (in the range 0.74–1.36 g cm^{-3}) had no detectable influence on the growth of young pines. Equally, previously completed research has shown that a negative influence on root growth most often occurs where the soil bulk density exceeds 1.40–1.45 g cm^{-3} [24].

A feature characteristic of natural regeneration during the early stages of development is a large number of seedlings and simultaneously high mortality rates [54]. Factors ensuring this type of mortality are high density of occurrence and associated competition, as well as the still-small sizes leaving seedlings vulnerable to competition with vegetation present at the clear-cut, unfavourable climatic conditions, disease, and damage resulting from insects and game animals [54–57]. In our trials, approximately 60% of all seedlings had survived for four years after the application of the different MSP methods, regardless of what treatment had been used. Factors seemingly encouraging the die-off of some seedlings in our experiment were unfavourable weather conditions (drought) as well as the impact of *Lophodermium* needle-cast, whose symptoms were observed during the spring of the third year of growth. During each season, there were months with insufficient rain, e.g., October of 2014; June, August and October of 2015; June and September of 2016 and May and June of 2017. The most severe drought conditions occurred during the August of the second year of growth, at which time the AI was just 2.76. Our result confirm that the greatest influence on seedling survival was that exerted by their density, with this in turn reflecting the MSP method applied (or lack of MSP). Higher seedling densities give rise to higher mortality.

5. Conclusions

Our research shows that natural regeneration of Scots pine can be achieved without using mechanical site preparation (MSP) methods, but that this is characterised by a low (15,000 seedlings ha^{-1}) and uneven density of trees (more than 50% of 1 m^2 plots without seedlings) making supplementary planting essential. MSP is thus needed for high-quality natural regeneration of the species. Practitioners in forestry are typically convinced that the FP (forest plough) method of MSP ensures the best natural regeneration of Scots pine, and the results of research completed to date have confirmed this [38]. However, this thesis is not supported by our work, which shows that the AP (active single-disc plough) method can ensure the highest densities and evenness of cover among pine seedlings. Rather more favourable parameters also characterise regeneration under the forest mill (FM) method, compared with the FP method. However, the strongest influence shaping the features of regeneration is a high precipitation total (of nearly 550 mm) during the first growing season that encouraged germination and early growth under both the AP and FM treatments. In these circumstances the FP and AP methods ensured better growth than that of the FM and no-MSP control. This leads to a general assertion that regeneration is mainly encouraged by MSPs on clear-cuts via a reduction in competition with other vegetation. This impact seems to be far more important than the capacity of different MSPs to produce differentiation in soil microhabitats, in terms of nutrient status or bulk density. Given that this is a short period of observation and results are derived from only one location, the recommendations for practice should rather be taken as preliminary.

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