SYLWAN 167 (3): 145-160, March 2023
https://doi.org/10.26202/sylwan.2023021
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

The effect of site preparation methods on the natural regeneration success of Scots pine *Pinus sylvestris* L. based on a report of a 4 year study

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ABSTRACT

Silvicultural site preparation creates a beneficial environment for tree regeneration and growth. Nowadays, new techniques and tools for mechanical site preparation are being investigated. On the one hand, they would disturb the soil environment as little as possible and, on the other, provide the best conditions for seed germination, seedling growth and survival. The aim of this study was to compare the effects of four mechanical site preparation methods: LPz OTL double mould-board forest plough (FP), single-disc active plough P1T (AP), forest soil grinder FL (FG) and slash piling rake ZPI (R) on the quality of natural regeneration of Scots pine grown under different habitat fertility conditions along with a control variant (C) without mechanical site preparation. The study was carried out in the Spychowo Forest District on three research areas (clear-cuts) which varied in terms of habitat fertility. Permanently marked transects (1 m wide) running across the entire width of the clear-cut and perpendicular to furrows or strips created as a result of site preparation were established on the clear-cuts. On these transects, in four consecutive years, the height of all pine trees was measured and assigned to successive square meters of trasects. The following parameters of natural regeneration of Scots pine were measured: seedlings height, density and evenness of coverage, and survival rate.

In the more fertile habitat, compared to the less fertile one, poorer natural regeneration was observed in terms of all the parameters analysed. The parameters of the natural regeneration observed in the control and rake variants, on all clear-cuts and regardless of the fertility of the habitat, indicate that without machanical site preparation or with minimal scarification regeneration with low and uneven density and poor growth will result. In the more fertile habitat, the best regeneration of Scots pine was achieved with active plough site preparation, while on the less fertile habitat the best results were obtained with the use of the forest soil grinder and forest plough. The local moisture conditions (the relatively high amount of rainfall) found in the Spychowo Forest District appear to have had the greatest influence on the observed results.

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Received: 18 April 2023; Revised: 19 May 2023; Accepted: 28 May 2023; Available online: 24 July 2023

KEY WORDS

clear-cut, habitat fertility, seedling density, seedling growth, seedling survival, self-sowing, soil scarification

Introduction

Scots pine *Pinus sylvestris* L., the main forest-forming species in Poland, can be regenerated naturally and artificially (Andrzejczyk and Żybura, 2012). Recently, natural regeneration of forest stands in Europe by self-sown seedlings has been practiced more frequently due to higher emphasis on 'close-to-nature' forest management (Lavnyy *et al.*, 2022). This is also the reason for an increase in the area of natural regeneration in Poland (Rozkrut, 2022). Natural conditions such as the dominance of conifer forest sites, the frequent occurrence of mast seed years (Tomczyk, 1993; Andrzejczyk *et al.*, 2009), and the belief that this type of regeneration method is better from both an ecological and economical point of view (Tomczyk, 1993; Andrzejczyk and Żybura, 2012) make the natural regeneration method more favourable.

Natural regeneration of pine on clear-cut sites has the greatest chance of the emergance and development on a fresh coniferous forest (highly oligotrophic) or a fresh mixed coniferous forest habitat (oligotrophic) (Andrzejczyk 2000; Andrzejczyk *et al.*, 2009). Although even in optimal habitats, natural regeneration of pine can sometimes be limited by grasses (Andrzejczyk and Żybura, 2012).

Some of the most important factors determining the success of natural regeneration of Scots pine are weather conditions (temperature and precipitation) during the period of seed germination and initial growth of seedlings (Oleskog and Sahlén, 2000; Puhlick *et al.*, 2012). Meteorological factors strongly contribute to soil moisture conditions.

A threat to achieving good quality Scots pine natural regeneration can be Lophodermium needle cast. A study by Andrzejczyk *et al.* (2009) showed that a stronger infection of seedlings occurs in the immediate vicinity of the stand and decreases in further zones of the clearcut as well as a decreasing degree of needle cast infection on the clearcut with an increasing age of seedlings.

Mechanical site preparation (MSP) of a regenerated forest area is a standard silvicultural activity preceding reforestation. It is widely used in Poland and around the world for both artificial and natural regeneration (ZHL, 2012; Saursaunet *et al.*, 2018). It aims to create favourable conditions for seed germination and seedling growth by, among other things: exposing the mineral soil and providing germinating seeds and seedlings access to soil moisture, reducing competition for water, light and nutrients from ground cover vegetation, and improving the physical and chemical properties of the soil (Drozdowski 2002; Andrzejczyk *et al.*, 2009; Andrzejczyk and Żybura, 2012).

MSP modifies such physical conditions of soil as water content, aeration, temperature and bulk density as well as chemical properties such as organic matter content, availability of nutrients and soil reactions (Archibold *et al.*, 2000; Block and Van Rees, 2002; MacKenzie *et al.*, 2005; Heiskanen *et al.*, 2007). An unfavourable result of MSP may be the leaching of mineral components leading to depletion of the soil (Lundmark-Thelin and Johansson, 1997; Piirainen *et al.*, 2007, 2009) and soil erosion if MSP is not adapted to the site-specific characteristics and climate (Alcázar *et al.*, 2002; Löf *et al.*, 2012). The influence of MSP on soil conditions as well as seedlings establishment and growth may vary in relation to climatic conditions, site-types and the types of species undergoing regeneration (Munson and Timmer, 1995; Mäkitalo, 1999; MacKenzie *et al.*, 2005; Löf *et al.*, 2012; Wallertz and Malmqvist, 2013).

Various techniques and tools are currently used for site preparation, which disturb the soil environment to varying degrees in terms of area and depth (Löf *et al*., 2012; Chaves Cardoso *et al*., 2020). Different site preparation techniques affect carbon storage with carbon amounts generally decreasing with an increasing tillage intensity (Fonseca *et al*., 2014).

In Poland, the traditional tool used for decades for MSP is the double mould-board forest plough. It exposes the mineral soil in a furrow creating a ridge containing ground cover vegetation, litter and a humus layer resulting in furrows and ridges covering 100% of the clear-cut area. The active plough and the forest grinder are tools with a much shorter history of use in Polish forestry. The active plough digs a parabolic-shaped furrow loosening the bottom of the furrow and covering it with mixed humus and mineral soil. On the ridge there is a partially mixed layer of humus, litter and ground cover vegetation. Furrows and ridges cover 80% of the clear-cut area with this type of MSP. The forest soil grinder grinds and mixes the ground cover vegetation, litter, humus layer and mineral soil to a depth of 30 cm in 40 cm wide strips, which covers 27% of the clear-cut area, and the soil between the strips remains undisturbed. (Neugebauer, 2008; Ośrodek Techniki Leśnej, 2022).

A number of studies indicate that an increase in the intensity of soil scarification leads to denser, more evenly distributed natural regeneration with better survival and growth of seedlings (Löf *et al*., 2012; Aleksandrowicz-Trzcińska *et al*., 2014, 2017b; Saursaunet *et al*., 2018). Andrzejczyk *et al*. (2003) demonstrated that in very oligotrophic habitats scarification should be gentle without disturbing the accumulation layer containing endohumus. Based on these habitat conditions, good results are obtained using an active plough and far worse results with the use of a double mould-board forest plough. In more fertile habitats (with greater pressure from ground cover vegetation) a more intensive treatment is advisable using the double mould-board forest plough (Andrzejczyk and Żybura, 2012). On the other hand, some studies carried out under Polish forest conditions indicate that in years of high precipitation less invasive MSP methods achieved better natural regeneration of Scots pine compared to more invasive ones (Aleksandrowicz-Trzcińska *et al*., 2017a, 2018a).

Nowadays, new techniques and tools for MSP are still being researched, which, on the one hand, interfere as little as possible with the soil environment and, on the other, provide the best conditions for seed germination, seedling growth and survival. An example of this would be the use of a slash piling rake to remove logging residues, which simultaneously scarifies the soil on the clear-cut. The aim of this study was to compare the effects on growth, density, uniformity, and survival rate of Scots pine regeneration grown under different habitat fertility conditions using the following four mechanical site preparation methods: LPz OTL double mould-board forest plough (FP), single-disc active plough P1T (AP), forest soil grinder FL (FG) and slash piling rake ZPI (R).

We hypothesized that the effectiveness of the method used would vary depending on the fertility of the habitat which would affect the parameters of pine natural regeneration in relation to differences in the rate of vegetation appearance and abundance on the clear-cut site as well as the availability of nutrients.

Materials and methods

The research was conducted in the Spychowo Forest District, Regional Directorate of State Forests in Olsztyn. The area of the Spychowo Forest District is located in the Central-Masurian Region with average values of meteorological factors for the Spychowo Forest District for the period of 2013-2022 shown in Table 1 (PUL, 2023).

The research was carried out on 3 clear-cuts established in 2016. The first represented the fresh mixed coniferous forest habitat – FMCF (oligotrophic, area1_FMFH) and the second and third the fresh coniferous forest habitat – FCF (very oligotrophic, area2_FCF, area3_FCF). The characteristics of the clear-cut study areas are shown in Table 2. Prior to site preparation the yield of pine cones was studied in line with the practice of the Spychowo Forest District by counting all cones collected from five cut down trees. There was an average yield of 232 cones per tree in Area1_FMCF, 231 cones in Area2_FCF, and 301 cones in Area3_FCF. The levels of the pine seeds crop in Spychowo Forest District are based on a scale as follows: up to 200 cones per tree indicating a poor crop, 201-400 an average crop, and above 400 cones a good crop.

MSP was performed using the following four types of machinery: LPz OTL double mould-board forest plough (FP), single-disc active plough P1T (AP), forest soil grinder FL (FG) and slash piling rake ZPI (R). The area of each clear-cut was divided into 5 experimental blocks and each block was divided into 5 plots, which correspond to 5 soil preparation method variants (as shown in Figure 1) in the experiment. The natural regeneration of Scots pine started in the spring of 2017. The adjacent stands acted as the seed source, which were located west or north west of the clear-cuts.

In the autumn of 2017, permanently marked transects were established. They were 1 m wide, ran perpendicular to the furrows or strips, and covered the entire width of the plot in the block. The total transect lengths for the variant was the following: from 72 m to 85 m in Area1_FMCF, from 67 to 76 m in Area2_FCF and from 143 to 167 m in Area3_FCF. In the autumn of four consecutive years (2017-2020) the heights of all pines along the transects were measured with positions assigned to the relevant meter distance along the transect.

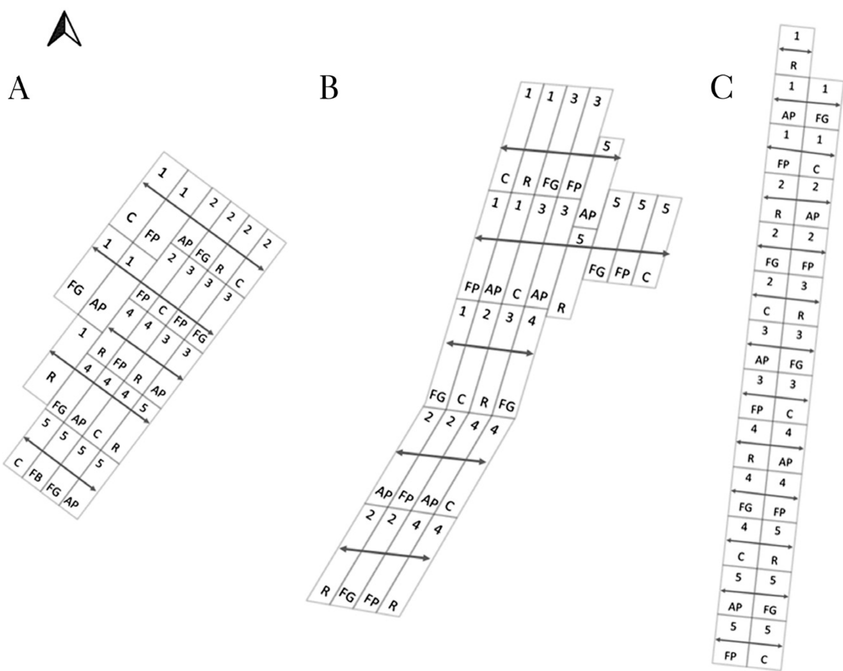


Fig. 1.

Experimental design

A – Area1_FMCF; B – Area2_FCF; C – Area3_FCF (FP – forest plough; AP – active plough; FG – forest soil grinder; R – slash piling rake; C – control, no-MSP; 1-5 blocks; arrows – transects)

Table 1.
Average values of meteorological factors for the period of 2013-2022. Data from the meteorological station in Olsztyn (PUL, 2023)

Meteorological factor	Month							Total or average for April-October
	April	May	June	July	August	September	October	
Average precipitation [mm]	30	58	69	94	67	68	60	634
Average temperature [°C]	7.8	13.1	17.6	18.6	18.6	13.6	9.0	14.0
Average wind speed [m/s]	2.84	2.68	2.75	2.73	2.03	2.51	2.82	2.62
Relative humidity [%]	66	68	70	73	65	79	83	72

Table 2.
Characteristics of clear-cut study plots

Name	Forest address geographic coordinates	Forest site types	Clear-cut area [ha]	Clear-cut width [m]	Soil type	Ground cover type	Stand before cutting
Area1_FMCF	07-24-2-06-23 -h -00 53°39'07.8"N 21°11'22.1"E	fresh mix coniferous forest	3.54	140	albic brunic arenosols	sodden	Pine 100%, 110 years old, average height 25 m, stand volume ca. 310 m^3 ha^{-1}
Area2_FCF	07-24-1-04-241 -d -01 53°33'33.7"N 21°19'49.9"E	fresh coniferoust fores	3.25	65	podzols	mossy	Pine 80%, spruce 20%, 110 years old, average height 25 m, stand volume ca. 350 m^3 ha^{-1}
Area3_FCF	07-24-2-08-251 -c -01 53°34'42.8"N 21°10'40.2"E	fresh coniferous forest	3.84	70	albic brunic arenosols	sodden	Pine 80%, spruce 20%, 115 years old, average height 25 m, stand volume ca. 300 m^3 ha^{-1}

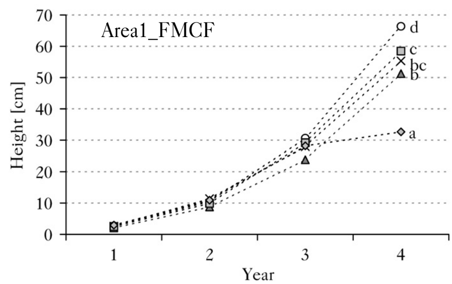
For these heights, densities of seedlings and survival rates for trees were used following a linear mixed model (LMM). In this model, the effect of one-meter quadrates nested in a block were considered random effects with the Tukey test used in 'post hoc' comparisons. For individual MSP methods (using percentages), we assessed the distribution of 1 m^2 plot frequencies in classes of seedling density designated as the following: '0' or 'zero plots' with no seedlings, '1' with 1-5 seedlings, '2' with 6-10 seedlings, and '3' with more than 10 seedlings. All statistical analyses were performed for each clear-cut separately using R version 4.2.1 (The R Foundation for Statistical Computing, Vienna, Austria),

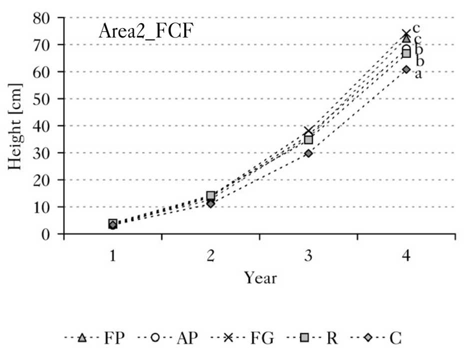
Results

Seedling height. On the clear-cuts of Area1_FMCF and Area2_FCF, tree height differentiation between variants started in the third year of growth and, additionally, in Area1_FMCF the differences increased in the fourth year. In Area3_FCF, differences in the height of the pines representing the different variants were statistically significant throughout the experiment. After 4 years on clear-cuts established in the FCF habitat (Area2 and Area3), the tallest were pines growing on soil scarified with FG and in the FMCF habitat using AP. After four years, pines from the control variant (without soil scarification) were statistically significant the lowest on all clear-cuts (Fig. 2).

Seedling density. On the clear-cut in Area1_FMCF, the highest seedling density during the whole experimental period was recorded in the variant using AP (4.9 seedlings/m^2 in the first year and 2.4 seedlings/m^2 in the last year), and on the clear-cut in Area3_FCF using FP (7.2 seedlings/m^2 in the first year and 4.2 seedlings/m^2 in the last year). In Area2_FCF for the variants using FP, AP and FG, seedlings density was similar and statistically higher compared to the other two variants (control and R in Figure 3).

Over the four years of the experiment, the statistically significantly lowest density of pine seedlings was found in all clear-cuts in the control variant without MSP. The highest density in this variant was recorded in the first year after sowing the seeds in Area1_FMCF (0.8 seedlings/m^2), and the lowest in the fourth year in the Area2_FCF (0.02 seedlings/m) (Fig. 3).





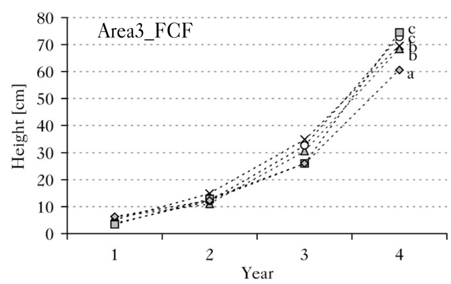


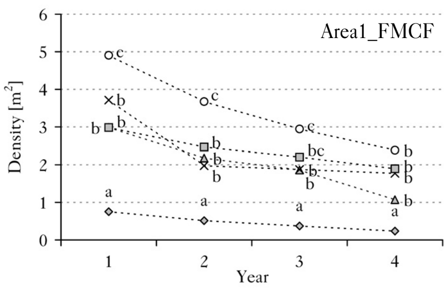
Fig. 2.

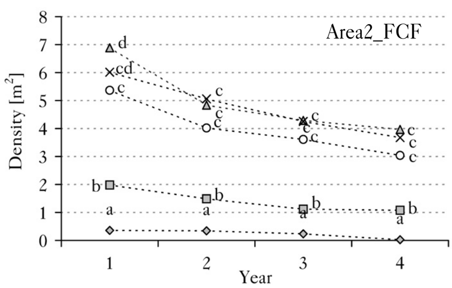
Mean height [cm] of Scots pine seedlings after 4 years in relation to the 4 MSP methods used

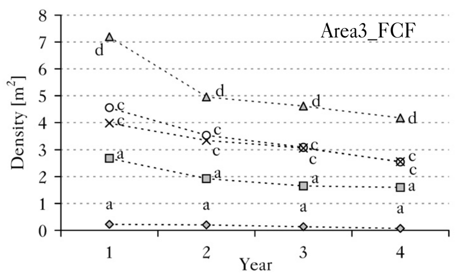
(FP – forest plough; AP – active plough; FG – forest soil grinder; R – slash piling rake; C – control, no-MSP). Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$

Seedling survival. In Area2_FCF and Area3_FCF (less fertile), during the 4 years of the experiment the highest survival rate was observed for seedlings growing on soil scarified with FG. In Area1_FMCF (more fertile), after the second year of growth there were no statistical differences in seedling survival. However, after the third and fourth year of growth, pine seedlings from the variants using FP, AP, FG and R had similar survival rates, but statistically significant differences from the control variant were found only for the R variant (Fig. 4).

Proportion of sample plots in density classes. In pine natural regeneration established in Area1_FMCF, the most favourable structure of one-meter sample plots was found in the variant using AP. The proportion of zero-plots (without seedlings) in this variant was 10.2%, plots with







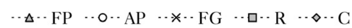
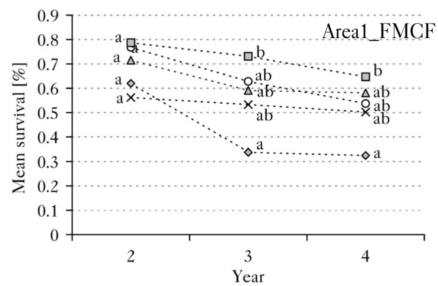
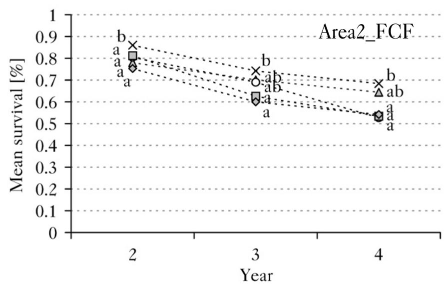


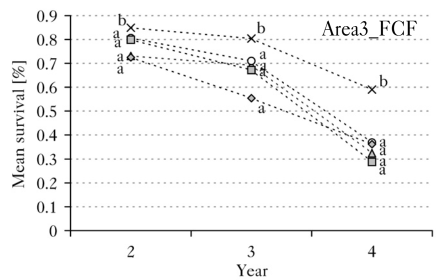
Fig. 3.

The average density [m^2] of Scots pine seedlings in relation to the 4 MSP methods used

(FP – forest plough; AP – active plough; FG – forest soil grinder; R – slash piling rake; C – control, no-MSP). Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$







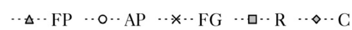


Fig. 4.

Mean survival [%] of Scots pine seedlings during 4 years in relation to 4 MSP methods

(FP – forest plough; AP – active plough; FG – forest soil grinder; R – slash piling rake; C – control, no-MSP). Different letters indicate significant differences obtained using the Tukey test, $p \leq 0.05$

number of seedlings in the range 6-10 was 24.8%, and plots with more than 10 seedlings was 3.7%. In the clear-cut Area2_FCF, the most favourable plot structures were characterised by the variant using FG and only slightly worse using FP. The opposite was true in Area3_FCF where the most favourable structure was recorded as a result of MSP using FP and slightly worse using FG.

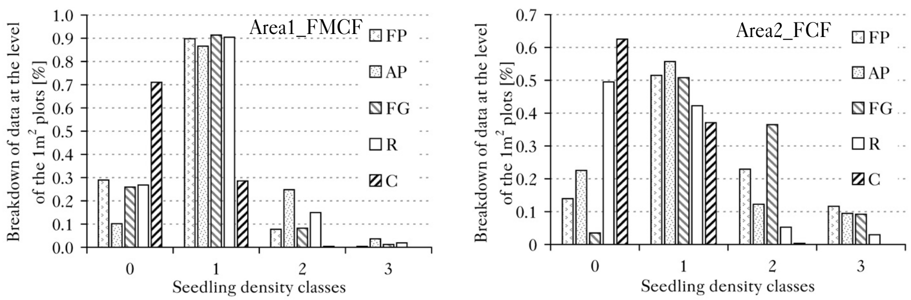
In all clear-cuts, the worst structure of the sample plots in all density classes was characterised by the control variant without MSP (percentage range of zero-plots from 62.5% in Area2_FCF to 75.2% in Area3_FCF). An unfavourable structure with a high proportion of zero-plots (from 26.8% to 49.5%) was also found as a result of soil scarification using R (Fig. 5).

Discussion

The results of our research answer the following question: which MSP methods make it possible to achieve good quality Scots pine natural regeneration with the least possible soil disturbance and dependent on the fertility of the habitat and the local conditions of the Spychowo Forest District.

In the more fertile habitat, FMCF (Area1_FMCF), AP was the most favourable soil scarification method. The natural regeneration in this variant had the highest density and the most favourable structure of sample plots in the density classes. Seedlings were taller compared to the ones from the other variants and their survival rate was similar to that of pines from the other variants. In the FCF habitat (less fertile) in Area2_FCF, comparable results were obtained from MSP using FP and FG, and in Area3_FCF using FP proved to be the most effective method of soil scarification. Only slightly weaker natural regeneration occurred on MSP using FG. Our results differ from those obtained by Andrzejczyk and Drozdowski (2003) which recommend AP soil preparation on less fertile sites and FP on more fertile ones.

The most important feature of natural regeneration is the density of seedlings and the evenness of their spatial distribution (Andrzejczyk and Żybura, 2012). The silvicultural value of natural regeneration is assessed with the use of a standard value to determine the average number of seedlings per 1 m^2 of regeneration. Until 2012, this value was defined by the Order of the Director General of the State Forests (Order No. 47A DGLP of 30.09.2015) and set at a value



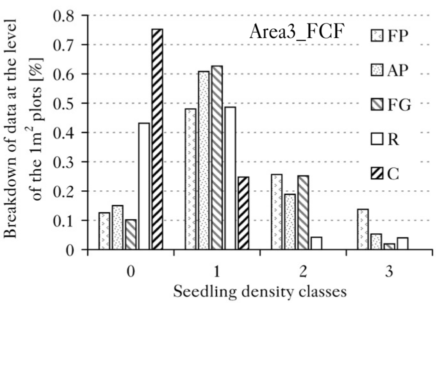


Fig. 5.

Sampling plot frequency [%] for Scots pine seedling density classes from four-year-old natural regeneration in relation to MSP methods

(FP – forest plough; AP – active plough; FG – forest soil grinder; R – slash piling rake; C – control, no-MSP). 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

of at least 5 seedlings/m^2. Since 2012 in order to simplify procedures and increase the possibility of the approval of natural regeneration, this standard value is set by the forest district manager (based on Order No. 58 DGLP of 31.08.2012). In the Spychowo Forest District, for natural regeneration of Scots pine up to 3 years of age, a minimum of 3 seedlings/m^2 has been used (Order DGLP No. 15/2012). Using this criteria in Area1_FMCF, natural regeneration with satisfactory density was only obtained in the variant using AP. In this case, such low densities can be explained by the shape of the clearcuts (140 m wide) resulting in the unfavourable distribution of the stands (the source of the seeds) and perhaps stronger development of ground cover vegetation compared to the two other clearcuts established in less fertile habitats. In the Area2_FCF and Area3_FCF, seedling densities of more than 3 seedlings/m^2 were achieved using FP, AP and FG site preparation. Thus, the lack of interference with the soil environment or only minimal scarification using R did not result in pine natural regeneration with satisfactory density. Korzeniewicz *et al.* (2016) claim that MSP performed using FP achieves pine natural regeneration density five times higher compared to treatments using AP. The discrepancy between the results obtained in our experiment and those of the aforementioned authors may have been influenced by factors other than MSP such as atmospheric conditions, soil conditions and seed yield. Most studies indicate that bare mineral soil is the optimal seedbed for the germination of forest tree seeds (Prévost, 1997; Béland *et al.*, 2000; Agestam *et al.*, 2003). Under these conditions the seed has better contact with the soil surface and better moisture conditions due to capillary water transport to the soil surface as compared to humus or organic substrates (Oleskog and Sahlén, 2000; de Chantal *et al.*, 2004). The results of our research only partially support this hypothesis as high seedling density (indicating good conditions for seed germination) was obtained not only from MSP using FP but also using AP and FG. This result is most likely due to local microclimatic conditions such as high precipitation during seed germination and the first weeks of seedling life (Puhlic *et al.*, 2012). 550 mm per year is the minimum average precipitation to achieve natural regeneration (Tomczyk, 1993) with average annual precipitation for the Spychowo Forest District being about 100 mm higher. This most likely provided sufficiently good moisture levels for the organic surface of the AP furrow and the FG belt. Previously, similar results were obtained in other experimental areas in the Spychowo Forest District (Aleksandrowicz-Trzcińska *et al.*, 2017a, 2018a).

The evenness of seedling density was assessed by the proportion of 1 m^2 sample plots in the density classes (Fig. 5). The high proportion of zero-plots (those without seedlings) may be indicative of high microhabitat diversity of the clear-cut surface areas (Karlsson and Nilson, 2005). In our experiment, however, it indicates a relationship between the evenness of seedling density and the method of MSP used. In each of the clear-cuts, the best structure of the sample plots in density classes (lowest percentage of zero-plots and highest in classes 2 and 3) were obtained by using different machinery as follows: in Area1_FMCF using AP, in Area2_FCF using FP, and in Area3_FCF using FG. This would indicate that the clear-cuts differed in other characteristics besides habitat fertility such as the shape of the clear-cuts and the distribution of sowing stands which may have influenced the results.

In the variant without the use of MSP, the proportion of zero-plots was very high (up to 75%). A slightly lower, but also high proportion, was found in the variant using R. These results indicate that natural regeneration occurring on clear-cuts with no site preparation or minimal scarification using R is characterised not only by low density, but also by uneven coverage. The results from our study are consistent with those obtained in other research (Karlsson and Örlander, 2000; Hille and den Ouden, 2004; Karlsson and Nilsson, 2005).

Without scarification the undisturbed soil cover consisted of some mosses, mainly *Hylocomium splendens* (Hedwig) Schimper. The field layer was composed of dwarf shrubs *Vaccinium myrillus* L., hairy wood-rush *Luzula pilosa* (L.)Willd. and other plants (PUL, 2013). This vegetation creates a heterogeneous surface and is known to provide conditions which are generally too dry for germination of pine seeds (Oleskog and Sahlén, 2000). Poor contact between seeds and unprepared soil, especially in places where the bottom layer consists of mosses, might have been the reason for low germination (Oleskog and Sahlén, 2000). Allelopathy may also inhibit seed germination in unprepared soil (Steijlen *et al.* 1995; Jäderlund *et al.* 1998) as the results showing a higher number of plots without seedlings in places where there is undisturbed soil, have also been found in other studies (Karlsson and Örlander, 2000; Karlsson *et al.* 2002). Due to the high share of zero-seedling plots, supplementary planting was needed (ZHL, 2012).

The fast growth of pine trees in the first years after regeneration is important to reduce damage from game and competition from ground cover vegetation on the clear-cuts (Bedford and Sutton, 2000). The growth rate of pine in the regeneration areas is dependent on a number of factors. Among the most important factors shaped by MSP include trophic conditions, humidity level, light intensity, and competition with ground cover vegetation (Örlander *et al.*, 1996; Nilsson and Örlander, 1999; MacKenzie *et al.*, 2005) with these factors working synergistically. Therefore, a deficit or excess of one of these can have a limiting effect on tree growth. Furthermore, although the different site preparation methods create different conditions for regenerative growth (MacKenzie *et al.*, 2005), their effect may vary depending on the characteristics of the regenerating species and local conditions such as habitat fertility and microclimatic conditions (Löf *et al.*, 2012; Wallertz and Malmqvist, 2013).

The height of pine trees after four years of growth in plantations was similar on both clear-cuts established in the FCF habitat (Area2 and Area3). In both cases, pine trees growing on sites prepared using FG were the tallest while pines from the variant using FP were slightly shorter but this result was not statistically significant. Pines growing on more fertile FMCF (Area1), were characterised by weaker growth with the tallest ones being from the variant using AP. Our results indicate that habitat fertility and soil nutrient content, which vary according to the MSP method used (Aleksandrowicz-Trzcińska *et al.*, 2018b), had no effect on the growth rate and therefore height of pines. Both on the poorest seedbeds *i.e.*, furrow mineral soil made using FP, and the poorer habitat FCF, the heights of pines were comparable or higher than in the variants where both seedbed and habitat were more fertile. It appears that the weaker growth in height of pine trees growing on the clear-cut in Area1_FMCF (more fertile habitat) may have been caused by more intensive vegetation growth in the clear-cut competing with pine for environmental resources as compared to the other two clear-cuts (Andrzejczyk and Żybura, 2012).

A characteristic feature of natural regeneration in the early stages of development is the high number of seedlings and their high mortality rate (Collet and Moguedec, 2007). Factors contributing to regeneration mortality include high seedling density, its associated competition, small seedling size, competition with clear-cut vegetation, adverse climatic conditions, disease, as well as insect and game damage (Akashi, 1997; Willoughby *et al.*, 2004; Collet and Moguedec, 2007; Rodriguez-Garcia *et al.*, 2011). In our experiment over a 4-year period, pine trees growing in Area2_FCF and Area3_FCF on MSP by FG had the highest survival rate. The pines from this variant were also the tallest, creating predominant competition for environmental resources. In the more fertile habitat (FMCF) such as Area1_FMCF, any soil scarification resulted in higher survival rates. As the density of pines was lowest here compared to the other two clear-cuts, it is likely that competition with ground cover vegetation had a greater impact on survival.

Our research only partially confirmed the hypothesis that more intensive scarification methods usually result in a higher initial number of seedlings, and therefore better subsequent growth and survival (Prévost, 1997; Mattsson and Bergsten, 2003; Nordborg and Nilsson, 2003; Bilodeau-Gauthier *et. al.*, 2011). Nor has the hypothesis been confirmed that in poorer habitats the scarification treatment should be gentle without disturbing the accumulation horizon containing endohumus. In these conditions, good results in terms of growth, survival and density can be obtained with the use of MSP by using AP and far worse results by using FP. In more fertile habitats with greater pressure from ground cover vegetation, a more intensive treatment should be used, such as FP (Andrzejczyk and Żybura, 2012). In our study, in the more fertile habitat the best-performing Scots pine regeneration was achieved through AP site preparation, while in the less fertile habitat the best results were obtained with the FG and FP variants. Obtaining these results is most likely related to the local moisture conditions found in the Spychowo Forest District due to the relatively high amount of precipitation (PUL, 2013) which provides favourable conditions for seed germination and seedlings growth (Aleksandrowicz-Trzcińska *et al.*, 2017a, 2018a).

The weakest pine regeneration was observed in the clear-cut in Area1_FMCF (more fertile). It was characterised with lower seedlings density, lower number of 1 m^2 sample plots in higher density classes (with more than 6 seedlings), and shorter height of pine in comparison with the regeneration achieved in less fertile habitats (Area2_FCF and Area3_FCF). This confirms the findings of earlier studies that in more fertile habitats there is a greater risk of not achieving a good quality pine regeneration mainly due to stronger competition from ground cover vegetation for environmental resources (Andrzejczyk *et al.*, 2009).

Our research is a case study with the results obtained confirming previous ones from the Spychowo Forest District but differing from those obtained in other regions of Poland (Korzeniewicz *et al.*, 2016; Aleksandrowicz-Trzcińska *et al.*, 2017b, 1918a).

Conclusion

In the conditions of the Spychowo Forest District in fresh mixed coniferous forest habitat, Scots pine natural regeneration with the best parameters (growth, survival, density and evenness of density) can be achieved as a result of site preparation with an active plough. In fresh coniferous forest habitat, on the other hand, the double mould-board forest plough and forest soil grinder will provide the best natural regeneration results.

Our research only partially confirmed the hypothesis that the use of more invasive MSP methods results in better Scots pine natural regeneration. It also confirmed the hypothesis that in poor habitats (fresh coniferous forest) better results will be obtained using an active plough (a less invasive method to the soil environment) than the double mould-board forest plough. Further, the hypothesis that more invasive methods (like the double mould-board forest plough) should be used in more fertile habitats (fresh mixed coniferous forest) was not confirmed.

Based on the results of this study, it can be concluded that the choice of mechanical site preparation method should be made with care and attention taking into account many factors such as habitat fertility, local moisture conditions and other factors. It is also important that the choice of soil scarification method should be adapted to the conditions of the specific forest district.

Authors' contributions

Conceptualization – H.Ż and M.A-T.; methodology – H.Ż. and M.A-T.; investigation – M.L. and A.C.; data curation – A.C., H.Ż. and M.S.; data analysis – M.S.; visualization – M.S.; writing manuscript – M.A-T. All authors read and approved manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

Funding and acknowledgments

The research received no external funding. The author extend their heartfelt thanks to the forest district manager of Spychowo Forest District, Krzysztof Krasula, MSc. Eng., as well as employees and trainees of the Forest District for their help in carrying out field work.

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STRESZCZENIE

Wpływ przygotowania gleby na sukces odnowienia naturalnego sosny zwyczajnej *Pinus sylvestris* L. – raport z 4-letnich badań

Sosna zwyczajna *Pinus sylvestris* L., główny gatunek lasotwórczy w Polsce, może być odnawiana naturalnie lub sztucznie. Mechaniczne przygotowanie gleby (MSP) odnawianej powierzchni leśnej jest standardową czynnością hodowlaną poprzedzającą odnowienie. Techniki i narzędzia do przygotowania gleby w różnym stopniu ingerują w środowisko glebowe: zarówno pod wzglę-

dem powierzchni, jak i głębokości. Celem pracy było porównanie wpływu 4 sposobów przygotowania gleby pod odnowienie naturalne sosny zwyczajnej w różnych warunkach żyzności siedliska (Bśw i BMśw): leśnym pługiem dwuodkładnicowym LPz (FP), jednotalerzowym pługiem aktywnym P1T (AP), frezem leśnym (FG) i zgrabiarką do gałęzi ZPI (R).

Badania realizowano na 3 zrębach zupełnych w Nadleśnictwie Spychowo. Pierwszy z nich reprezentował siedlisko BMśw (area1_FMCF), a drugi i trzeci Bśw (area2_FCF i area3_FCF) (tab. 2). Na każdym zrębie glebę przygotowano 4 narzędziami, a porównanie stanowił wariant kontrolny (C), bez przygotowania gleby. Pomiary przeprowadzono na trwale oznaczonych transektach o szerokości 1 m, biegnących prostopadle do bruzd lub pasów i obejmujących całą szerokość zrębu (ryc. 1). W 4 kolejnych latach (2017-2020) pomierzono wysokość wszystkich siewek, przyporządkowując je do kolejnych metrów kwadratowych transektów. Na zrębach założonych na siedlisku Bśw (area2_FCF i area3_FCF) po 4 latach najwyższe były sosny rosnące na glebie przygotowanej frezem (odpowiednio 74,1 i 74,5 cm), a na siedlisku BMśw – pługiem aktywnym (66,4 cm). Po 4 latach na wszystkich zrębach istotnie statystycznie najniższe były sosny z wariantu kontrolnego, bez przygotowania gleby (ryc. 2). Na żyźniejszym siedlisku (BMśw) na powierzchni area1_FMCF najwyższe zagęszczenie siewek przez cały okres trwania doświadczenia odnotowano na glebie przygotowanej pługiem aktywnym (po 4 latach 2,4 szt./m^2), a na mniej żyznym (Bśw) na powierzchni area3_FCF – pługiem LPz (po 4 latach 4,2 szt./m^2). Na powierzchni area2_FCF (siedlisko Bśw) w wariantach z pługiem LPz, pługiem aktywnym i frezem zagęszczenie odnowienia było zbliżone i statystycznie wyższe w porównaniu z 2 pozostałymi wariantami (kontrola i zgrabiarka). W ciągu 4 lat trwania doświadczenia na wszystkich zrębach istotnie statystycznie najniższe zagęszczenie sosen stwierdzano w wariancie kontrolnym, bez przygotowania gleby (ryc. 3).

Na powierzchniach area2_FCF i area3_FCF w ciągu 4 lat trwania doświadczenia najwyższą przeżywalnością charakteryzowały się siewki rosnące na glebie przygotowanej frezem (po 4 latach odpowiednio 0,68 i 0,59%). Na powierzchni area1_FMCF zbliżoną przeżywalnością charakteryzowały się sosny z wariantów z pługiem LPz, pługiem aktywnym, frezem i zgrabiarką. Różnice istotne statystycznie w stosunku do kontroli stwierdzono jednak tylko w odniesieniu do wariantu ze zgrabiarką (ryc. 4).

W odnowieniu powstałym na powierzchni area1_FMCF najkorzystniejszą strukturę jednometrowych powierzchni próbnych (najniższy udział powierzchni „zerowych" – bez siewek i najwyższy udział powierzchni w 3 i 4 klasie zagęszczenia siewek) stwierdzono w wariancie z przygotowaniem gleby pługiem aktywnym. Na powierzchni area2_FCF najkorzystniejszą strukturą poletek charakteryzował się wariant z przygotowaniem gleby frezem i tylko nieco gorszą pługiem LPz. Odwrotna sytuacja występowała na powierzchni area3_FCF, gdzie najkorzystniejszą strukturę odnotowano w wyniku przygotowania gleby pługiem LPz, a nieco gorszą przy użyciu frezu (ryc. 5).

Na żyźniejszym siedlisku odnowienie o najlepszych parametrach uzyskano w wyniku przygotowania gleby pługiem aktywnym, a na mniej żyznym najlepsze efekty odnotowano w wariantach z frezem i pługiem LPz. Wydaje się, że największy wpływ na uzyskanie takich wyników miały lokalne warunki wilgotnościowe występujące w Nadleśnictwie Spychowo (tab. 1). Stosunkowo wysoka ilość opadów zapewniła porównywalne lub lepsze warunki do kiełkowania nasion i wzrostu siewek (w porównaniu z glebą mineralną dna bruzdy wykonanej LPz) na podłożu organicznym, w metodach mniej ingerujących w środowisko glebowe (pług aktywny i frez). Na żyźniejszym siedlisku uzyskano w porównaniu z mniej żyznym słabsze odnowienie pod względem wszystkich analizowanych parametrów. Najprawdopodobniej jest to związane z obecnością bardziej obfitej roślinności na zrębie i wynikającej stąd silniejszej konkurencji ze strony runa o zasoby środowiska.

Parametry odnowień naturalnych uzyskanych w wariantach kontrolnym (C) i z użyciem grabi (R) na wszystkich zrębach, bez względu na żyzność siedliska, wskazują, że bez przygotowania gleby lub z minimalną skaryfikacją uzyskuje się odnowienie o niskim i nierównomiernym zagęszczeniu oraz słabym wzroście.