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Effect of logging residue removal and mechanical site preparation on productivity of the subsequent Scots pine (*Pinus sylvestris* L.) stands

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Abstract

Key message Removal of logging residue negatively affected tree diameter and height, but had no significant effect on the basal area of the subsequent stand (in the mid-term). On the other hand, different methods of mechanical site preparation (bedding, plowing furrows, and trenching) had no effect on tree growth 1 year after planting, but had a significant effect on tree diameter, tree height, and basal area in the mid-term. Bedding treatments could have a significant positive impact on the productivity of the subsequent Scots pine stands, even when planted on sandy, free-draining soils.

Context Increased use of logging residues in forests may address the growing demand for renewable energy. However, concerns have arisen regarding the depletion of the forest soil, resulting in a decrease in the productivity of the next forest generation. Identifying the drivers of forest growth may be the key to understanding the relationship between logging residue removal and stand productivity.

Aims Quantifying the effect of three mechanical site preparation methods (bedding, plowing furrows, and trenching) combined with five methods of logging residue management (complete removal, comminution, incineration, leaving whole, comminution with, and without mixing with topsoil) on growth of subsequent Scots pine stands, 1 year and 12 years after planting.

Methods The experiment was set up as a randomized complete block design of 45 plots with three replications of combinations of three mechanical site preparation methods and five logging residue treatment methods.

Results The effects of the different methods of mechanical site preparation were not significant 1 year after planting but bedding treatment caused increase in DBH, tree height, and basal area after 12 years. Various methods of logging residue management did not cause any differences in the survival rate nor the basal area of the next-generation stands; however, there was a significant influence on tree sizes. Moreover, the effects changed with time; in plots

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with a complete removal of logging residues, the trees were the highest 1 year after planting, but after 12 years, their height and DBH were the lowest.

Conclusions It can be concluded that bedding treatments could have a significant positive impact on the productivity of the subsequent Scots pine stands. No effect found of different logging residue treatments on the productivity of Scots pine stands further confirms that the increased removal of biomass from the forest environment does not necessarily result in its rapid degradation. Observations at longer term are however needed to obtain the full spectrum of responses to logging residue removal.

Keywords Whole-tree harvesting, Soil productivity, Tree growth, Nutrient removal, Seedling survival

1 Introduction

The international demand for renewable energy continues to increase (Jastad et al., 2020; Cintas et al., 2021), and there is a growing interest in the use of forest biomass as a possible replacement for fossil fuels (Clarke et al., 2021; James et al., 2021). One way to increase the utilization of biomass in managed forests is the use of logging residues, the tree components that are conventionally left in the forest, such as branches, foliage, tree tops, small diameter trees, and technically damaged trees (Achat et al., 2015; Ranius et al., 2018). However, removing more biomass and nutrients has several potential environmental impacts (Paré and Thiffault, 2016; Ranius et al., 2018). Nutrient concentrations in logging residues are high, which might increase the risk of a nutrient imbalance and reduce forest production over time (Vanguelova et al., 2010; Helmisaari et al., 2011; Egnell, 2017).

The risk of soil depletion and decreased productivity of the next generation of trees has spurred numerous studies. One research approach has focused on nutrient budget calculations. Comparisons of the amounts of nutrients exported by harvesting with natural inputs (rainfall and weathering) and outputs (stream water) have produced no definitive results. Some input-output comparisons have indicated that the nutrient balance is negative if whole-tree harvesting (including logging residues) is practiced (Carey, 1980; Olsson et al., 2000; Joki-Heiskala et al., 2003; Akselsson et al., 2007). Others have suggested that the input-output balance of most nutrients could be positive, especially for N (Helmisaari, 1995; Merino et al., 2005; Brandtberg and Olsson, 2012).

The second research approach has focused on evaluating the effects of harvest removal on nutrient dynamics. Many studies have confirmed that the intensive removal of forest residues can affect nutrient fluxes in the soil (Wall, 2008; Achat et al., 2015; Wan et al., 2018; Clarke et al., 2021). However, recent reviews have indicated limited or only short-term impacts of increased biomass removal on the soil nutrient stocks and concentrations (Thiffault et al., 2011; Ranius et al., 2018; Morris et al., 2019; James et al., 2021).

The third research approach has directly measured productivity, expressed as tree height, diameter, or biomass of the subsequent stands. The growth results have been provided by numerous studies from the experiment networks established as the North American long-term soil productivity study (Powers et al., 2005; Fleming et al., 2006; Ponder et al., 2012) and experiment networks in northern Europe (UK and Scandinavia) (Proe et al., 1999; Luiro et al., 2010; Egnell, 2011; Helmisaari et al., 2011; Tveite and Hanssen, 2013). Some studies have found evidence of decreased second rotation productivity resulting from residue removal during whole-tree harvesting when compared with stem-only harvesting (Jacobson et al., 2000; Egnell and Valinger, 2003; Walmsley et al., 2009; Helmisaari et al., 2011; Achat et al., 2015). However, other experiments showed that residue removal had no detectable effect on the productivity of the following stand (Powers et al., 2005; Sanchez et al., 2006; Tan et al., 2009; Saarsalmi et al., 2010; Roxby and Howard, 2013). Reviews and meta-analyses conducted have concluded that there is no consensus result on the effects of harvesting forest biomass on soil productivity (Thiffault et al., 2011; Wall, 2012; Achat et al., 2015; Egnell, 2017; Ranius et al., 2018).

The actual response of forest ecosystems to residue removal may only be loosely related to the export of nutrients caused by the harvesting methods. Forest productivity appears to be driven by more complex factors and interactions than simple nutrient input-output balances (Paré and Thiffault, 2016; Premer et al., 2019). Identifying these factors may be the key to understanding the relationship between logging residue removal and stand productivity. For example, several studies have reported site- and species-specific interactions related to whole-tree harvesting (Thiffault et al., 2006; Smolander et al., 2015; Egnell, 2017; Wan et al., 2018). However, because different tree species are often associated with different habitats, it may not be possible to determine whether the effect depends on either the tree species or soil properties (Clarke et al., 2021).

A critical covariable of site sensitivity to whole-tree harvesting may also be the location, as there are clear regional differences in factors such as climate, soil type, and nutrient deposition. Some reviews have reported disparities in tree growth between European and North American trials (Thiffault et al., 2011; Tveite and Hanssen, 2013; Achat et al., 2015). Variations have also been found between southern and northern Sweden (Egnell, 2017). Clarke et al. (2021). However, one problem is the unbalanced data distribution; generally, the USA, Sweden, and Finland are over-represented in forest growth experiments (Achat et al., 2015).

Site preparation could be another key driver of soil productivity. Different methods of mechanical site preparation may significantly affect the growth and survival of seedlings (Örlander et al., 1996; Mäkitalo, 1999; Nilsson et al., 2019; Sikström et al., 2020). Site preparation improves site conditions by reducing the competing ground vegetation (Nilsson and Örlander, 1999; Archibold et al., 2000), while increasing the nutrient mineralization (Schmidt et al., 1996; Nohrstedt, 2000), water availability (Löf et al., 2012), and soil temperature (Simard et al., 2003) and improving aeration at wet sites (Kabrick et al., 2005; Nilsson et al., 2019). However, different methods of mechanical site preparation can have a positive or negative effect on the growth and survival of seedlings. This can be influenced by factors such as site fertility, soil drying, water-logging, vegetation competition, soil compaction due to the machinery, or threats from the pine weevils (*Hylobius abietis* L.) (Wallertz et al., 2018; Celma et al., 2019; Sikström et al., 2020; Ugawa et al., 2020). For example, in waterlogged soils, trenching may increase waterlogging even further while bedding is likely to decrease it. In dry soils, on the other hand, trenching will improve water availability and bedding will decrease it (Hope, 2007; Löf et al., 2012; Nilsson et al., 2019).

Many studies have confirmed the short-term effects of different methods of mechanical site preparation on seedling height in northern Europe (Örlander et al., 2002; Hallsby and Örlander, 2004; Petersson et al., 2005; Wallertz et al., 2018) and North America (Graham et al., 1989; Aust et al., 1998; Xu et al., 2000; Simard et al., 2003). Similarly, the long-term effects of MSP on tree height have also been confirmed in northern Europe (Örlander et al., 1996; Mäkitalo, 1999; Johansson et al., 2013; Hjelm et al., 2019) and North America (Bedford et al., 2000; Kyle et al., 2005; Prévost and Dumais, 2018). In contrast, no such effect was identified for Scots pine in Sweden 18 years after planting (Hansson and Karlman, 1997).

In the present paper, we report the results of a mid-term experiment on the simultaneous effects of two factors (site preparation and logging residue treatment) on the survival and growth of Scots pine (*Pinus sylvestris* L.) stands. The experiment was conducted in Central Europe (Poland), a region where the Scots pine is the most economically significant tree species (Węgiel et al., 2018; Sewerniak, 2020).

The aim of this study was to investigate the effects of three methods of mechanical site preparation and five logging residue treatments on the subsequent stands 1 year and 12 years after planting.

We tested the following hypotheses:

1) One year after planting, mechanical site preparation has a stronger effect on the survival and growth of trees than logging residue treatment.
2) Twelve years after planting, logging residue treatment has a stronger effect on the stand growth than mechanical site preparation.
3) The removal of logging residue negatively affects mid-term stand productivity.

2 Material and methods

2.1 Study area

The study area is located in northern Poland (53° 33' N, 16° 56' E) in the Okonek Forest District (Fig. 1). The dominant tree species is Scots pine (*Pinus sylvestris* L.), and the stands are managed by the State Forests National Forest Holding according to the forest management plan (FMP, 2020). The average annual temperature is 8.2 °C, total rainfall is 615 mm, and vegetation period is 213 days.

The area is dominated by Albic Brunic Arenosols (IUSS Working Group WRB, 2015) with a uniform soil texture (sand). The thickness of the O horizon is 6 cm on average, and the thickness of the AE and B horizons are 15 and 43 cm, respectively. Due to sand texture, these soils are permeable to water, and no groundwater was found to the depth of 200 cm. Seasonal flooding and waterlogging have not occurred. The site index was 21.2 m at a base age of 100 years (Socha et al., 2020). The study area of 2.8 ha was covered by a 103-year-old Scots pine forest, with an average diameter at breast height (DBH) of 29.1 cm and an average height of 21.5 m. During a clear cut in January 2004, 619 m^3 of timber was procured (221 m^3 per ha). The dry biomass and

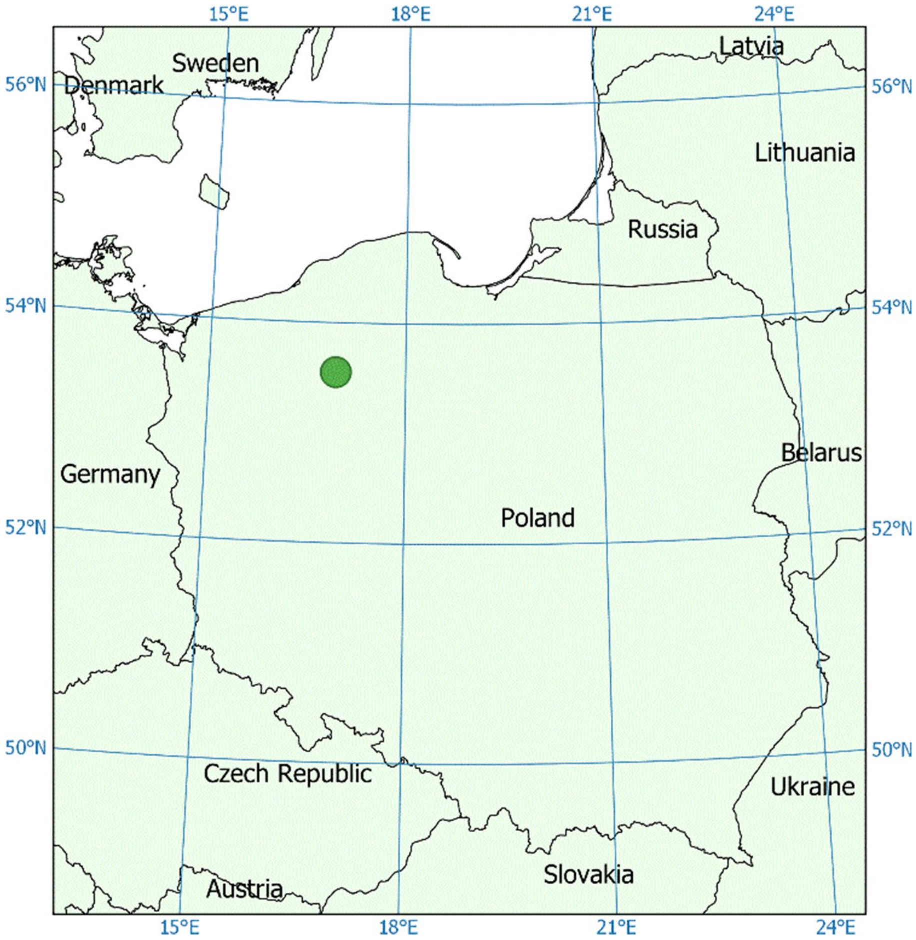

Fig. 1 The experimental design and location of sample plot. The letters (**A**–**C**) indicate different variants of mechanical site preparation, and the numbers (1–5) indicate different variants of the logging residue treatment

Table 1 Dry biomass and macronutrient content of the pre-harvest 102-year-old Scots pine stand

	Dry biomass [Mg ha^{-1}]	Macronutrient stock [kg ha^{-1}]				
		N	P	K	Ca	Mg
Stem wood	114.1	191.3	19.8	29.7	120.1	20.0
Stem bark	15.4	48.7	3.7	12.2	104.4	6.9
Branches	9.6	27.8	2.1	8.6	27.3	2.8
Foliage	3.9	54.6	9.6	20.6	14.1	2.3
TOTAL	143.0	322.4	35.2	71.1	265.9	32.0

macronutrient stock distributions of the various tree categories are listed in Table 1. Site preparation took place in autumn 2004 and stand establishment in spring 2005. Pine seedlings were planted using the hand bar-slit method with a density that is traditional for Polish conditions of approximately 10 thousand per ha (spacing 70 × 140 cm).

2.2 Experiment design

The study area was divided into 45 plots (approximately 400 m^2 each) as a randomized complete block design with three replications of combinations of three mechanical site preparation methods and five logging residue treatment methods (Fig. 1).

Mechanical site preparation methods employed were as follows:

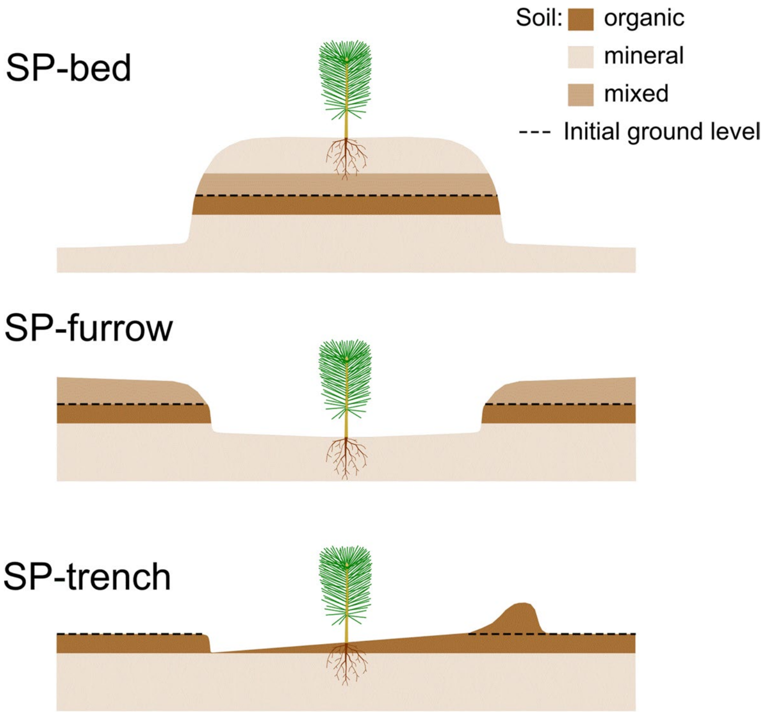

Fig. 2 Schematic description of three types of mechanical site preparation: bedding and planting on ridges (SP-bed), plowing and planting in furrows (SP-furrow), and disc trenching (SP-trench)

A – Bedding and planting on ridges (later referred to as SP-bed), where the soil was plowed twice with an LPz-75 V-plow (manufactured by the Center for Forest Technology in Jarocin, Poland), thus creating a raised bed (Fig. 2, top).

B – Plowing and planting in furrows (SP-furrow), where the soil was plowed once using an LPz-75 V-plow (Fig. 2, middle).

C – Disc trenching (SP-trench), where the soil was scarified with an active disc plow U-162 (Center for Forest Technology in Jarocin, Poland) and the trees were planted in the shallow furrow (Fig. 2, bottom).

Logging residue treatments were as follows:

1. Complete removal, where all the logging residues were thoroughly lifted and manually carried outside the (later referred to as LR-1).
2. Incineration, where all the logging residues were lifted and burned on small heaps inside the plot (LR-2).
3. Leaving whole, where all the logging residues were left spread evenly on the ground, and only the longest branches were cut into large pieces (LR-3).
4. Comminution and leaving on the surface, where the logging residues were crushed using a DVV-96 crusher (Center for Forest Technology in Jarocin, Poland) (LR-4).
5. Comminution and mixing with topsoil, where the logging residues were crushed using a DVV-96 crusher and mixed with topsoil with a disc harrow (LR-5).

One year after planting, the survival rate and average height of the seedlings were recorded (Jakubowski et al. 2022). Every fourth row was selected for study, where the seedlings were counted, and their height was measured from the ground level up to the top bud. In 2016, the growth and number of trees were measured again. DBH was measured for all trees, and the height of every fifth tree was measured (Jakubowski et al. 2022). Based on these data, stand density and basal area were calculated. No cleaning or thinning was performed, also no fungicide or insecticide spraying was performed during the study period.

2.3 Statistical analyses

Before the statistical analysis, the data were tested for normality using the Kolmogorov-Smirnov test and homoscedasticity using the Box-Cox transformation.

A two-way ANOVA was conducted to determine the influence of the site preparation method and logging residue treatment on the survival of seedlings, tree height, DBH, stand density, and basal area. An ANOVA with dependent variables was conducted to determine the influence of time. When significant differences in the response variables were detected, they were identified using Tukey's post hoc test for multiple comparisons.

Differences were considered statistically significant at $p < 0.05$. All the analysis procedures were conducted using Statistica 13.1 (StatSoft Polska, Poland).

3 Results

The mean seedling survival ranged from 85.9 to 89.1%, 1 year after planting (Table 2). No significant differences were found for either the mechanical site preparation methods or logging residue treatments. The mean tree heights ranged from 9.1 to 9.6 cm. There were slight differences ($p = 0.0403$) between the different logging residue treatments. The mean tree height was higher for LR-1 (complete removal) than for LR-3 (leaving whole on surface), whereas no significant differences in tree height were found among the site preparation methods (Tables 2 and 3).

Twelve years after planting, significant differences were found among the site preparation methods in the DBH, tree height, stand density, and basal area (Fig. 3, Table 3). DBH and tree height were significantly different among all the site preparation methods ($p < 0.0001$). Both were highest for the SP-bed and lowest for the SP-trench. The stand density was highest for the SP-bed and differed significantly from the SP-trench ($p = 0.0178$), but not from SP-furrow. Basal area was highest for the SP-bed and differed significantly from the SP-furrow and SP-trench at $p < 0.0001$.

Significant differences among the various treatments of logging residues (12 years after planting) were found for DBH and tree height (Fig. 4, Table 3). Both were highest for LR-5 and lowest for LR-1 ($p < 0.0001$ and $p = 0.0113$ for DBH and tree height, respectively).

Table 3 Results of ANOVA, presenting the *p* values for the effects of mechanical site preparation and logging residue treatment on seedling survival, DBH (diameter at breast height), tree height, basal area, and stand density of sampled Scots pines 1 year and 12 years after planting

Source of variation	**Mechanical site preparation**		**Logging residue treatment**	
	1 year after planting	**12 years after planting**	**1 year after planting**	**12 years after planting**
Survival of seedlings	ns	-	ns	-
Tree height	ns	***	*	**
DBH	-	***	-	***
Stand density	-	*	-	ns
Basal area	-	***	-	ns

*Significant at $p < 0.05$. **Significant at $p < 0.01$. ***Significant at $p < 0.001$, *ns* not significant

The two-way ANOVA indicated that there was no effect of the interaction between mechanical site preparation and logging residue treatment on the tree height, DBH, and basal area, even though each factor separately affected these variables (Table 4). Tukey's test for multiple comparisons showed that variant C1 (SP-trench and LR-1) with a mean basal area of 10.8 m^2 was lower than the other variants, 11.8 to 16.2 m^2 (Fig. 5).

4 Discussion

Twelve years after planting, mechanical site preparation had an impact on seedling survival and growth. Scots pines planted on ridges (SP-bed) had significantly greater DBH, height, and basal area than those planted on non-elevated spots (SP-furrow and SP-trench). Planting on raised beds may be beneficial for initial tree growth on waterlogged soils. Bedding improves the air-water balance near the seedlings by increasing aeration and by elevating the seedlings higher above the water table (Aust et al., 1998; Eisenbies et al., 2004). Many studies have

Table 2 Survival and height of Scots pine seedlings 1 year after planting. Different letters indicate significant differences in tree heights among the logging residue treatments ($p < 0.05$)

	Mean survival of seedlings ± SD [%]	**Mean height ± SD [cm]**
Mechanical site preparation		
Bedding and planting on ridges (SP-bed)	89.1 ± 3.6	9.4 ± 2.9
Plowing and planting in furrows (SP-furrow)	86.1 ± 6.4	9.3 ± 3.3
Disc trenching (SP-trench)	88.2 ± 3.3	9.2 ± 3.0
Logging residue treatment		
Complete removal (LR-1)	89.1 ± 5.4	9.6 ± 3.4 b
Incineration (LR-2)	86.4 ± 6.3	9.4 ± 3.0 ab
Leaving whole on surface (LR-3)	85.9 ± 2.6	9.1 ± 3.1 a
Comminution and leaving on surface (LR-4)	88.1 ± 5.4	9.2 ± 3.1 ab
Comminution and mixing with topsoil (LR-5)	89.0 ± 4.3	9.3 ± 3.1 ab

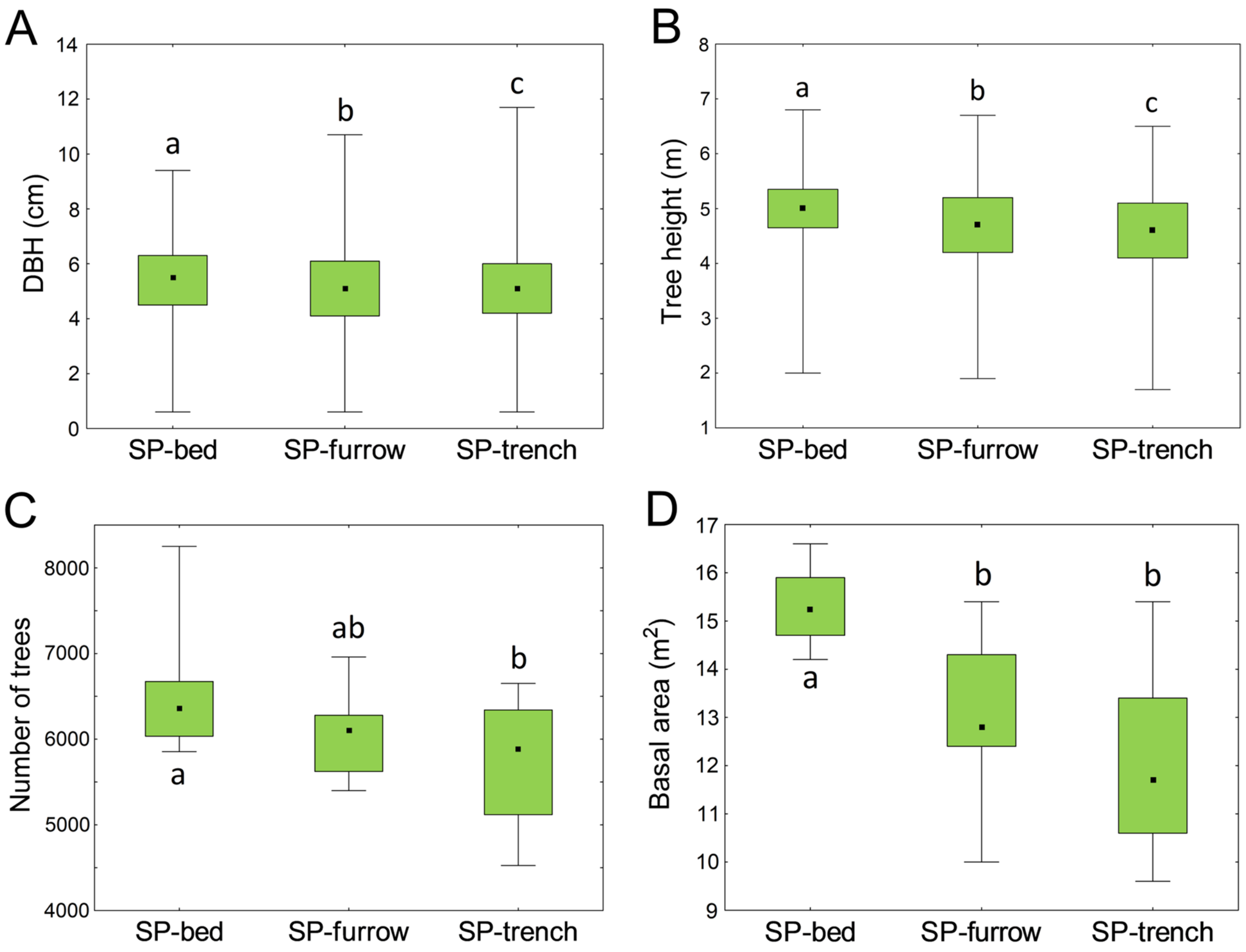

Fig. 3 Mean (±95% confidence interval) DBH (**A**), tree height (**B**), number of trees (**C**), and basal area (**D**) for three methods of site preparation: bedding and planting on ridges (SP-bed), plowing and planting in furrows (SP-furrow), and disc trenching (SP-trench), 12 years after planting. The results of the ANOVA are presented. Different letters indicate significant differences (Tukey's honestly significant difference test) among methods of site preparation ($p < 0.05$)

confirmed that bedding creates better growth conditions for seedlings on wet soils than other treatments (Graham et al., 1989; Hansson and Karlman, 1997; Bedford et al., 2000; Boateng et al., 2006; Heiskanen et al., 2013). However, our experiment was conducted on free draining sandy soils, where bedding treatment was not expected to be beneficial because there was no waterlogging conditions to alleviate. Furthermore, elevating planting spots could create poorer growth conditions for seedlings due to possible water scarcity (Löf et al., 2012; Sikström et al., 2020). Nonetheless, other advantages of bedding, not only on waterlogged soils, include increased soil temperature, increased nutrient availability and uptake, reduced soil bulk density, improved soil aeration, and reduction in vegetation competition (Aust et al., 1998; Bedford and Sutton, 2000; Eisenbies et al., 2004; Löf et al., 2012; Neaves et al., 2017). As our study was conducted on poor sandy soils, nutrient availability was likely to have the greatest impact on the differences found in the compared mechanical site preparation. SP-bed had created elevated planting spots of mixed organic and mineral soil, where a much higher nutrient content was expected than for SP-furrow and SP-trench. In Canada, Bedford and Sutton (2000) also found that lodgepole pine (*Pinus contorta* Dougl. ex Loud.) 10 years after planting on low fertility and low water-holding soil achieved the greatest height increment on bedding and mounding compared to other treatments. In Latvia, Celma et al. (2019) reported that Norway spruce (*Picea abies* (L.) Karst.) and Scots pine, 1–3 years after planting on soils of varying fertility and varying soil moisture, are forming deeper root systems when planted on mounds.

Our results demonstrate that the effect of site preparation on seedling survival and growth varied 1 year after planting from that in the longer term. Mechanical site preparation significantly affected both tree growth (DBH,

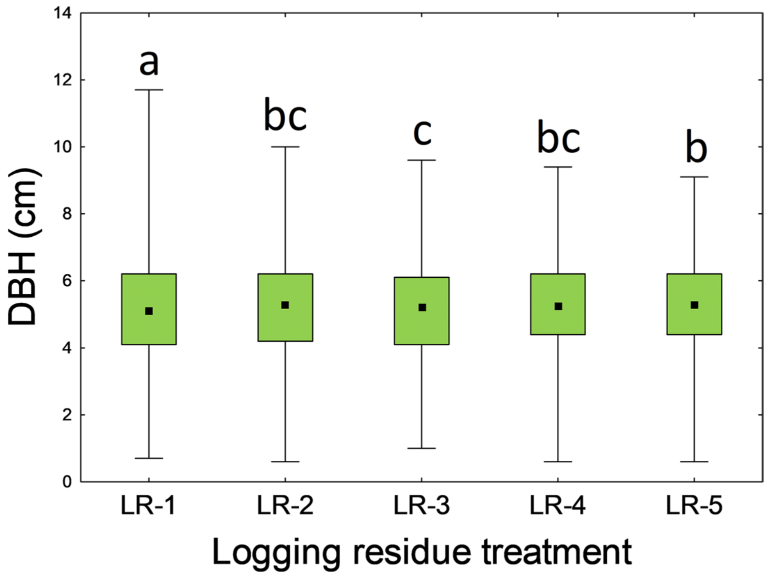

Fig. 4 Mean (±95% confidence interval) DBH for five logging residue treatments (at 12 years of age): complete removal (LR-1), incineration (LR-2), leaving whole on surface (LR-3), comminution and leaving on surface (LR-4), and comminution and mixing with topsoil (LR-5). Results of the ANOVA are presented. Different letters indicate significant differences (Tukey's honestly significant difference test) among methods of site preparation ($p < 0.05$)

Table 4 Results of two-way ANOVA, presenting the effects of mechanical site preparation (MSP), logging residue treatment (LR), and their interactions on tree height, DBH, and basal area of sampled Scots pines 12 years after planting

Source of variation	Tree height				DBH				Basal area			
	Df	MS	*F*	*p*	Df	MS	*F*	*p*	Df	MS	*F*	*p*
MSP	2	34.5	50.0	<0.0001	2	193.3	89.6	<0.0001	2	40.1	18.3	<0.0001
LR	4	0.6	0.8	0.4979	4	11.0	5.1	0.0004	4	1.4	0.6	0.6425
MSP x LR	8	0.4	0.5	0.8466	8	2.4	1.1	0.3466	8	1.3	0.6	0.7898
Error	2.7	0.7			11.0	2.2			29	2.2		

height, and basal area) and stand density 12 years after planting, whereas 1 year after planting no such effect was observed. We expected that site preparation would have a strong effect on seedlings in the short term, with little or no effect in the mid-term. Our results do not support Hypotheses 1 or 2.

An explanation for the differences between the short- and mid-term effects of mechanical site preparation on trees could be the alteration of soil processes affecting nutrient availability in free draining soils. At first, the bedding treatment caused mixing of the organic matter and it caused temporary immobilization of nutrient mineralization, but later on (when the C to N ratio stabilized), enhanced nutrient mineralization. Confirmation can be found in a study by Andrzejczyk and Drozdowski (2003), who compared the quality of natural regeneration of Scots pine on furrows and ridges conducted on the same soil type in Poland. In the first year, greater height and survival of seedlings growing in furrows was observed, but, in the following years, the situation was reversed, with greater height and survival rates for trees growing on ridges.

The short-term effect of mechanical site preparation (mounding, scarifying, trenching, subsoiling) on seedling survival (1–3 years after planting) has been reported for Norway spruce and Scots pine in Sweden under dry to moist soil moisture (Örlander et al., 2002; Hallsby and Örlander, 2004; Wallertz et al., 2018; Nilsson et al., 2019), Norway spruce in Russia under mesic moisture conditions (Novichonok et al., 2020), and lodgepole pine and white spruce (*Picea glauca* (Moench) Voss) in Canada under submesic to mesic moisture regime (Simard et al., 2003; Boateng et al., 2006). In contrast, 3 years after planting, mechanical site preparation had no effect on the survival of Norway spruce in Sweden under mesic soil moisture (Petersson et al., 2005) or of Douglas-fir

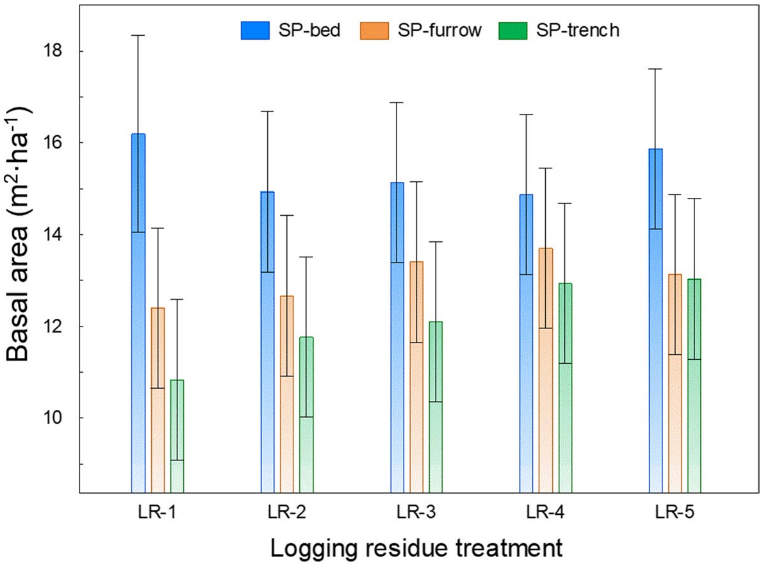

Fig. 5 Mean (±95% confidence interval) basal area (at 12 years of age) for five logging residue treatments: complete removal (LR-1), incineration (LR-2), leaving whole on surface (LR-3), comminution and leaving on surface (LR-4), and comminution and mixing with topsoil (LR-5), and three methods of site preparation: bedding and planting on ridges (SP-bed), plowing and planting in furrows (SP-furrow), and disc trenching (SP-trench)

(*Pseudotsuga menziesii* (Mirb.) Franco) in the USA (Graham et al., 1989). Long-term effects (more than 10 years after planting) of mechanical site preparation on seedling survival under different soil moisture conditions have been reported (Hansson and Karlman, 1997; Örlander et al., 1998; Mäkitalo, 1999; Bedford et al., 2000; Johansson et al., 2013), and mechanical site preparation affected the stand density even 30 years after planting on sites of varying fertility and soil moisture in Sweden (Örlander et al., 1996; Hjelm et al., 2019). In contrast, Kyle et al. (2005) found no such effect for loblolly pine (*Pinus taeda* L.) 33 years after planting on wet sandy soils in the Coastal Plain of Virginia (USA).

It should be noted that our short- and medium-term results are of limited applicability, as the tree growth responses to mechanical site preparation may be temporary. Some studies indicate that the effect of site preparation treatments on tree growth diminishes with time (Kyle et al., 2005; Zhao et al., 2009; Ramirez et al., 2022). It has been reported that growth responses to mechanical site preparation are significant during the first 10–15 years after planting (Hansson and Karlman, 1997; Johansson et al., 2013). After that, the height differences probably persist, but without further increases (Sikström et al., 2020). In the longest experiment conducted on coarse-textured soils in Sweden, Örlander et al. (1996) found no long-term effects of site preparation 70 years after establishment.

We found no effect of different logging residue treatments on seedling survival, which is consistent with many other studies (Achat et al., 2015; Egnell, 2017). We also found that the effect of logging residue treatment on tree growth was different 1 year after planting from that in the longer term. Surprisingly, the tree-height results exhibited the opposite trend. One year after planting, the tree height in plots where the logging residues were removed (LR-1) was the highest and 12 years after planting it was the lowest. The observed effect may be because the influence of logging residue management on tree productivity in the first years following harvest is mostly related to the physical effects of the residues on the soil environment and not to nutritional changes (Paré and Thiffault, 2016). At a very early stage of stand development, the presence of residues onsite may increase the light and water availability for the tree seedlings (Harrington et al., 2013). Soil water availability may also be affected by the sheltering effect of residues that limit evaporation but intercepts precipitation (Roberts et al., 2005). Furthermore, the presence of logging residues can decrease soil temperature (Trottier-Picard et al., 2014). In our experiment, 1 year after planting, the significant differences between LR-1 (completely removed LR) and LR-3 (left LR whole on surface) may confirm that, during this time, seedling growth is more affected by the soil environment than by nutrient availability.

Similar to our results, some previous studies have reported differences in short- and long-term effects. For example, logging residue removal significantly affected Norway spruce 10–31 years after planting (Egnell, 2011) and Scots pine 15–25 year after planting (Egnell and

Valinger, 2003). Both of these studies found no short-term effects (less than 10 years after planting). In a review of Nordic studies summarizing data from 72 experimental sites, Egnell (2017) analyzed the effects of biomass harvest intensity on the subsequent forest production. He determined that most of the studies that demonstrated significant effects on the site and stand productivity following a slash harvest used observation periods longer than 10 years.

In contrast, Achat et al. (2015) quantified the consequences of removing harvesting residues from forest soils and tree growth in meta-analyses of published data representing 749 case studies worldwide and determined that there was no significant effect after an elapsed time (two classes studied: 0–10 years and >10 years), but the data suggested stronger positive or negative impacts during the first years after harvesting. Ranius et al. (2018) reviewed 279 scientific papers that compared logging residues extraction with non-extraction. The studies were split into those presenting data <10 years or >10 years after treatment, and this split did not change the overall result, with the majority of experiments observing no effects of logging residue extraction on ecosystem services and biodiversity.

Existing experiments have presented only short- to mid-term effects of harvest residue removals on site productivity. Additional long-term studies are desirable, to detect possible effects on subsequent stands (covering one complete rotation) and cumulative impacts from experiments where residues have been harvested multiple times (Kaarakka et al., 2014; Egnell, 2017; Clarke et al., 2021). Although there are some evidence suggesting that the effect of harvest residues on site productivity were generally reduced with time but were likely to last for several decades (Egnell, 2011; Achat et al., 2015; Clarke et al., 2021).

Notably, in our experiment, the significant effect of different logging residue treatments was only on the tree size (tree diameter and height). However, the logging residue treatments had no effect on the basal area. In a stand, many small trees or a few large trees result in the same basal area, volume, and biomass, indicating that the basal area is a more valuable factor than tree size in determining the effect on stand productivity. Thus, we have not confirmed Hypothesis 3 that the removal of logging residue negatively affects mid-term stand productivity.

The two-way ANOVA indicated no effect of the interaction between logging residue treatment and mechanical site preparation in our experiment, even though each factor separately affected the tree height, diameter and basal area. However, it is worth noting that the combination of SP-trench and LR-1 with the smallest average basal area differed significantly from the other cases. This may have implications for forest management, trenching removes topsoil and may limit nutrient mineralisation, and when coupled to LR-1 (residue removal), it may affect trees even more severely.

A similar experiment on the same two factors was conducted in southern Sweden for Norway spruce, Scots pine, and lodgepole pine on sites of varying fertility and soil moisture (Hjelm et al., 2019). The researchers had aimed to investigate the effects of site preparation treatments and slash removal on long-term productivity. They found that slash removal had no significant negative effects on the long-term productivity, but mechanical site preparation increased both the survival and early growth of the planted seedlings, as well as increased production in terms of standing volume approximately 30 years after planting. There was a tendency in the experiment towards higher production with increasing site preparation intensity, with disc trenching seen as the least intensive method and ploughing as the most intensive method regarding soil disturbance (Hjelm et al., 2019).

Most European experiments on the effects of logging residue removal on the subsequent stand growth have been conducted in Nordic countries (Achat et al., 2015; Sikström et al., 2020; Clarke et al., 2021), where nitrogen deposition is limited (Paré and Thiffault, 2016; Lim et al., 2020). The results of these experiments cannot be directly extrapolated to other parts of Europe, where the levels of N deposition vary considerably (Schwede et al., 2018; Schmitz et al., 2019). The simulations determined that the critical N load (an exposure to pollutants below which significant harmful effects do not occur) was exceeded in 84% of the European forested areas (Im et al., 2013). In areas with high levels of anthropogenic N deposition, nutrient export from harvested biomass can have positive effects on the forest environment (Börjesson, 2000; Hedwall et al., 2013). Therefore, it is necessary to conduct additional studies in different parts of Europe.

5 Conclusions

Based on our results, we can draw the following conclusions:

1. Bedding treatments could have a significant positive impact on the productivity of the subsequent Scots pine stands, even when planted on sandy, free-draining soils, many years after planting. This is worth considering when establishing new plantations.
2. We found no effect of different logging residue treatments on the productivity of Scots pine stands. This further confirms that the increased removal of biomass from the forest environment does not necessarily result in its degradation. Greater use of logging residues in forests should also be considered outside the Nordic countries where this is already common.

However, one should be careful, as some combinations of site preparation and logging residue treatment (such as trenching and residue removal) may mutually reinforce negative impacts on the soil productivity.

3. The significant differences between the short-term and mid-term results for both the different mechanical site preparation methods and the logging residue treatments indicates that conclusions of short-term forest experiments should be made carefully. It is critical to continue existing experiments and establish additional long-term forest experiments for various tree species in different regions.

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Code availability (software application or custom code)
Not applicable

Authors' contributions
Conceptualization: Roman Gornowicz; Methodology: Roman Gornowicz and Andrzej Węgiel; Formal analysis and investigation: Andrzej Węgiel, Marta Molińska-Glura, Krzysztof Polowy, Jolanta Węgiel, and Roman Gornowicz; Writing—original draft preparation: Andrzej Węgiel; Writing—review and editing: Andrzej Węgiel, Marta Molińska-Glura, and Krzysztof Polowy; Funding acquisition: Jakub Jakubowski; Supervision: Roman Gornowicz. The authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

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Competing interests
The authors declare that they have no competing interests.

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