SILVA FENNICA

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Influence of mechanical site preparation on regeneration success of planted conifers in clearcuts in Fennoscandia – a review

Highlights

- Mechanical site preparation (MSP) increases seedling survival rates by 15–20%.
- Survival rates of 80–90% ca. 10 years after MSP and planting conifers are possible.
- MSP can increase tree height 10–15 years after planting by 10–25%.
- The increase in growth rate associated with MSP may be temporary, but the height enhancement probably persists.

Abstract

In the Nordic countries Finland, Norway and Sweden, the most common regeneration method is planting after clearcutting and, often, mechanical site preparation (MSP). The main focus of this study is to review quantitative effects that have been reported for the five main MSP methods in terms of survival and growth of manually planted coniferous seedlings of Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in clearcuts in these three countries. Meta analyses are used to compare the effects of MSP methods to control areas where there was no MSP and identify any relationships with temperature sum and number of years after planting. In addition, the area of disturbed soil surface and the emergence of naturally regenerated seedlings are evaluated. The MSP methods considered are patch scarification, disc trenching, mounding, soil inversion and ploughing. Studies performed at sites with predominately mineral soils (with an organic topsoil no thicker than 0.30 m), in boreal, nemo-boreal and nemoral vegetation zones in the three Fenno-Scandinavian countries are included in the review. Data from 26 experimental and five survey studies in total were compiled and evaluated. The results show that survival rates of planted conifers at sites where seedlings are not strongly affected by pine weevil (*Hylobius abietis* L.) are generally 80–90% after MSP, and 15–20 percent units higher than after planting in non-prepared sites. The experimental data indicated that soil inversion and potentially ploughing (few studies) give marginally greater rates than the other methods in this respect. The effects of MSP on survival seem to be independent of the temperature sum. Below 800 degree days, however, the reported survival rates are more variable. MSP generally results in trees 10–25% taller 10–15 years after planting compared to no MSP. The strength of the growth effect appears to be inversely related to the temperature sum. The compiled data may assist in the design, evaluation and comparison of possible regeneration chains, i.e. analyses of the efficiency and cost-effectiveness of multiple combinations of reforestation measures.

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1 Introduction

Successful, cost-efficient reforestation is essential for sustainable forest production, particularly in intensive forestry regimes intended to provide high yields and deliver forest biomass products. Thus, in the Nordic countries of Finland, Norway and Sweden, forest regeneration is always mandatory after final felling of a stand on forest land (Forskrift om berekraftig skogbruk 2006; Finnish Forest act 1093/1996 and amendments up to 567/2014 2014; Skogsstyrelsen 2017). The most common regeneration method is planting, undertaken on approximately 65% of the total regenerated area in Finland and Norway, and 80% of the area in Sweden. Norway spruce (*Picea abies* (L.) Karst.) seedlings are most commonly used, although Scots pine (*Pinus sylvestris* L.) seedlings are also planted. In Finland and Sweden, mechanical site preparation (MSP) is often undertaken at the regeneration stage. Disc trenching or mounding are mainly used, but patch scarification is also quite common (see section 2). During the last 10 years, the total areas subjected to MSP per year amounted to 100 000–120 000 ha in Finland and 160 000–190 000 ha in Sweden (Luke 2018; Skogsstyrelsen 2018). In Norway, the corresponding areas are modest (5000–7000 ha annually; ca. 20% of the regenerated areas (Granhus et al. 2016)), mainly due to a higher proportion of steep and rocky terrain but also the lack of tradition and scarcity of equipment. High mortality rates of planted seedlings have been recorded in practical forestry, sometimes in spite of MSP being undertaken (Persson 1990; Ackzell et al. 1994; Bergquist et al. 2011; Söderbäck 2012). As planted seedlings are often genetically improved and quite costly, it is important to exploit the benefits of MSP and increase cost-effectiveness in regeneration operations.

The purpose of site preparation prior to planting is to provide favourable planting spots for seedling establishment, but also to increase the efficiency of the planting procedure. Seedling survival and growth are improved by removing the top organic soil layer and exposing the bare mineral soil or a mixture of organic matter and mineral soil (Örlander et al. 1990). Several factors that limit the seedlings´ survival and growth are affected by MSP, for instance vegetation competition, soil temperature and soil moisture. Soil temperature can be substantially increased by removal of the humus layer, and the MSP-effect on soil temperature sums, i.e. the accumulated temperature above a defined threshold temperature (usually 5 °C) during a defined period, show large differences among different MSP methods. For example, at a depth of 10 cm a difference of 230 degree days has been shown between a ploughed ridge and untreated soil, in Fennoscandia corresponding to a 4° shift in latitude or 200 m in elevation (Örlander et al. 1990). Other likely effects are increased mineralization rates and nutrient availability for planted seedlings, although these are dependent on the selected planting spot. Potentially, the MSP-effect on soil temperature sum affects seedling survival and growth to a greater extent in a harsh climate (cf. Sutton 1993). In addition, MSP affects soil structure and interactions with herbivores, notably pine weevil feeding on planted seedlings. Numerous scientific studies have reported beneficial effects of various types of MSP on survival and growth of planted conifers in Fennoscandia (Hansson and Karlman 1997; Mäkitalo 1999; Johansson et al. 2013a) and boreal forests in North America (Bedford and Sutton 2000; Simard et al. 2003; Thiffault et al. 2010).

High mortality of planted seedlings may be a problem, and there are numerous reasons for the mortality of planted seedlings in clearcuts. For example, the causes may be due to low quality of seedlings from the nursery, suboptimal handling during transport and storage, poor quality of chosen planting spots and planting procedures being poorly executed (cf. Grossnickle 2012; Grossnickle and MacDonald 2018). Various stressors may also severely affect planted seedlings, notably feeding by pine weevils (*Hylobius abietis* L.), which is a major threat if not prevented (Nordlander et al. 2011). Insufficient or incorrect site preparation may also contribute (directly or indirectly) to seedling mortality, for example by causing soil conditions that are too dry or too moist (Sutton 1993; Löf et al. 2012) and increasing frost heaving (de Chantal et al. 2007). Seedling mortality is, however, usually reduced by MSP prior to regeneration and the measure is an important step for successful stand establishment (Hansson and Karlman 1997; Mäkitalo 1999; Johansson et al. 2013a). Therefore, the importance of properly applying appropriate methods must be stressed.

The effects of site preparation on the establishment of naturally regenerated seedlings, mainly broadleaves, have also been addressed (Karlsson et al. 2002; Lehtosalo et al. 2010; Johansson et al. 2013a). Naturally regenerated seedlings comprise a large proportion (20–30%) of future conifer crop trees in plantations (Ackzell et al. 1994; Kullström 2015) but at same time naturally regenerated seedlings, especially broadleaves, are the main reason for the need for pre-commercial thinning operations. Many of the MSP methods used today cause extensive soil disturbance (Pohtila and Pohjola 1985; Hallsby and Örlander 2004). For several reasons, it is important to minimize the area with disturbed topsoil, since disturbance results in the emergence of unwanted natural regeneration, increases soil erosion in susceptible areas, and is undesirable aesthetically. Thus, an optimal compromise that provides enough suitable planting spots but minimizes undesirable disturbance is suggested.

In current operational forestry, the focus is often on minimizing the cost of each regeneration measure rather than optimizing the cost-effectiveness of the entire "regeneration chain", which commonly includes site preparation, planting and pre-commercial thinning (Sikström et al. 2018). The latter is not straightforward: Uotila et al. (2010) found indications of interactions between site preparation methods and later forest management measures that may influence the profitability of possible regeneration chains. Thus, for robust analyses, detailed knowledge of the effects of possible silvicultural measures are needed, including effects of potential site preparation methods on the survival and growth of planted coniferous seedlings. Knowledge of their effects on the emergence of natural regeneration, both broadleaves and conifers, is also needed to predict future pre-commercial thinning needs and costs.

Previous published reviews of MSP have addressed biological and physical aspects (Örlander et al. 1990; Sutton 1993), the latter focusing mainly on experiences of several types of mounding. Löf et al. (2012) synthesized the current state-of-knowledge concerning MSP applied to improve tree establishment in forest restoration efforts on various types of land, such as former farmlands, very dry sites and mine sites. Prévost (1992) reviewed current knowledge about the effects of site preparation on, for example, the establishment and growth of seedlings, mainly based on North American studies relevant to conditions in Québec province, Canada. Moreover, there are regional guidelines, which commonly include fundamental principles for site preparation and advice for selection of methods and use of equipment depending on site conditions (von der Gönna 1992; Sutherland and Foreman 1995). The cited reviews have provided valuable information. However, to our knowledge, there is no comprehensive compilation and analysis of reported quantitative effects of MSPs on planted seedlings' survival and growth rates, the amount of disturbed soil surface or the emergence of natural regeneration. This review is intended to compile such data and analyse it.

1.1 Aim and scope

The main aim of this study is to review, collate and analyse reported quantitative effects of five mechanical site preparation (MSP) methods on the survival and growth of planted coniferous seedlings, disturbed soil surface areas, and natural regeneration densities. The MSP methods considered are patch scarification, disc trenching, mounding, soil inversion and ploughing (see section 2). MSP effects, i.e. the differences in results between the MSP methods and planting with no MSP (control areas), are also considered in meta analyses in relation to temperature sum and number of years after planting, as well as in statistical analyses comparing the MSP methods.

The review is restricted to field studies conducted in the boreal, nemo-boreal and nemoral vegetation zones (Ahti et al. 1968) of Finland, Norway and Sweden. Only studies covering at least three growing seasons from the time of planting, at sites with mineral soil (having an organic top layer no thicker than 0.30 m), are included. The study focuses largely on Scots pine, Norway spruce and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) seedlings. In the discussion, findings from studies conducted in North American vegetation zones with silvicultural conditions similar to those of Fennoscandia are also considered in order to place the results in a wider context.

2 The studied MSP methods

MSP is conducted prior to the establishment of a new stand in every rotation. The MSP-methods evaluated are described briefly below and have been described in more detail by Örlander et al. (1990).

No mechanical site preparation (*No MSP*) refers to planting after no or minor soil disturbance by logging machinery (Fig. 1). If necessary, to facilitate planting, the top soil layer (humus) may be disturbed in a small spot using a planting tool or by foot.

In *patch scarification* the humus layer is removed and left next to the resulting patches of bare mineral soil (Fig. 1). Since only the upper organic layer of the soil is removed, patch scarification seldom loosens the underlying mineral soil in which the seedlings are planted. The patches are often situated below ground level. Therefore, the method is mostly used on dry sites with relatively low fertility or on very stony sites where other MSP methods cannot be employed.

Disc trenching produces furrows and berms (Fig. 1). The furrows represent similar planting spots to the patches, but in continuous rows. The berms provide elevated planting spots consisting of mineral soil above a double humus layer, in which seedlings can also be planted. Other possible planting positions are on the hinges between furrows and berms. The choice of planting position usually depends on the specific site conditions and results of the disc trenching. The method can be applied to all types of mineral soils, and works well on stony sites, but is not appropriate for moist sites.

Mounding creates elevated planting spots surrounded by minimally disturbed soil, composed of mineral soil, usually on top of a double, inverted humus layer (Fig. 1), comparable to the berms created by disc trenching. The mounds may also be placed on patches with bare mineral soil instead of on inverted humus layers. At some sites, materials from excavated ditches are used to form mounds, and these are usually predominantly composed of mineral soil but may contain some organic matter (humus). The method tends to be employed on mesic to moist sites, where elevated planting spots are advantageous for seedling survival.

Soil inversion refers to the creation of planting spots with mineral soil on top of an inverted humus layer (Fig. 1). The inverted material is replaced in the indentation it was taken from, so the planting spots are usually in level with the surrounding ground. This method can be employed at
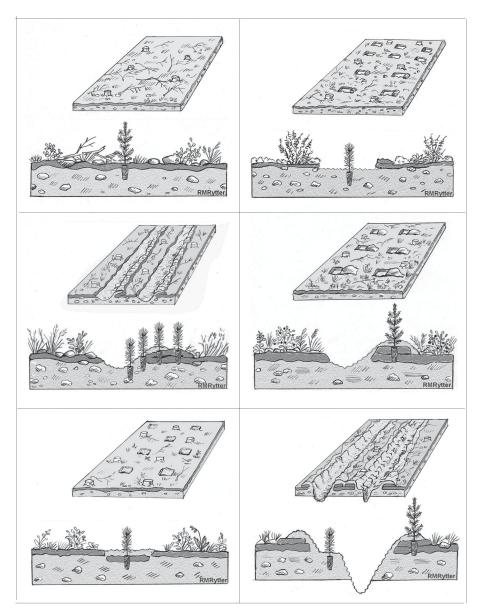
Fig. 1. Schematic illustrations of site preparation methods considered in the study. Planting with no site preparation (No MSP; top left), and after; patch scarification (top right), disc trenching (middle left), mounding (middle right), soil inversion (bottom left) and ploughing (bottom right). For further explanation, see section 2. Illustrations are made by Rose-Marie Rytter.

most sites, but not in very dry or very moist soil conditions due to cutting off capillary water at dry sites and the need for an elevated planting spot at very moist sites.

Ploughing generates deep furrows beside thick continuous ridges of mineral soil on top of double humus layers (Fig. 1). Seedlings are often planted on top of the ridges, or in pure mineral soil on terraces next to the furrows created by certain ploughs (Fig. 1). Since ploughing displaces soil, it is now rarely used in the Nordic countries and is not permitted on operational forest land in Sweden, but it may still be used for research purposes. The method was mainly used on large clearcuts with moist soils having low nutrient availability (often due to low soil temperatures).

3   Materials and methods

3.1 Literature search

The literature reviewed included scientific articles in peer-reviewed journals and relevant technical reports (international and national) of studies with well-documented experimental designs, measurements, and accurate data analysis.

The peer-reviewed scientific articles included were identified by searching the Web of Science database for published studies on relevant phenomena, defined more broadly than in the aims and scope of this review specified above (section 1.1). Key-words used in the searches included "site preparation" and "conifer seedlings", and "research area" was defined as "forestry". This yielded 455 articles. After reading abstracts of these articles, those that met the criteria set out in the aims and scope of the review were selected. The literature included in the study that was not peer-reviewed, such as reports, were found by reading reference lists of other publications, scanning databases and libraries of our host research organizations (SLU, NIBIO, LUKE and Skogforsk), and through personal contacts with other researchers. We found 30 articles or reports (hereafter "germane studies") that met the criteria for this review (see sections 1.1 and 3.2) and were included in the compilation of quantitative effects of MSPs on survival and growth of planted seedlings (Tables 1 and 2). Twenty-six of these included data from field experiments and five included data from surveys (hereafter surveys) of stands established in operational forestry. Data from three of the surveys were based on measurements in permanent plots within operational regeneration sites with known initial seedling density and height at planting (Luoranen et al. 2006; Saksa 2011; Söderbäck 2012), whereas two of the surveys were measurements carried out once in temporary plots at operational regeneration sites (Saksa et al. 2005; Saksa and Kankaanhuhta 2007). Data on disturbed soil surface areas resulting from site preparation and on natural regeneration densities were found in 12 and eight studies, respectively.

3.2 Data compilation and meta analyses

Only data obtained from studies involving MSP and planting in clearcuts, in which results were collected at least three years after planting, were included. The three-year limit was set since, in general, most of the seedling mortality after planting occurs during the first two–three years, irrespective of whether MSP has been undertaken, yielding more robust data on survival rates in our data set (cf. Elfving 1992). Data on treatments and results obtained using shelterwood or continuous cover silvicultural systems were excluded. For each experimental study involving one or several field experiments, data pertaining to the following variables were collated: tree species, the number of growing seasons from planting to monitoring (years after planting), the survival rate and height of seedlings associated with each studied MSP method at the time of monitoring, numbers of experimental sites, approximate locations (latitude, altitude) of the sites, and corresponding temperature sums. If more than one experimental site was included in a study, a mean value for the temperature sum was calculated and used in further analyses. Data on the same variables were collated for the surveys, with the exception of temperature sum.

For the Swedish field experiments, the temperature sum was estimated using functions presented by Morén and Perttu (1994). For the Norwegian field experiments, the Norwegian Meteorological Institute (NMI) provided temperature sum data. The temperature data in the period 1960–1990 were extracted from a 1 km × 1 km climate grid, with interpolations of relevant variables based on measurements from climate stations established and maintained by NMI (Lussana et al. 2016). For the Finnish sites, temperature data were obtained from the database of the Finnish

Table 1. Survival rates (%) of planted Norway spruce (Ns), Scots pine (Sp) and lodgepole pine (Lp) seedlings following each mechanical site preparation method (MSP) and No MSP, in field experiments and survey studies obtained 3–27 growing seasons after planting. The character ~ indicates values estimated from a diagram and * in "No MSP" that statistical analysis was reported in that study. Bold values indicate a statistically significant difference from the control ("No MSP") and values in brackets show differences in percentage units in relation to "No MSP". In most experiments, the planted seedlings were protected by an insecticide to reduce pine weevil (*Hylobius abietis* L.) damage. In experiments where both protected and unprotected seedlings were planted values are shown for both types.

Tree species	Years after planting	Latitude (°N)	Altitude (m a.s.l.)	Temp. sum (d.d. °C)	Survival (%) by MSP-method						No. of sites	Reference
					No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing		
Experiments												
Ns[2]	3	60	200	1116	~67*	**~91** (+24)		**~91** (+24)			1	Brække et al. (1986)
Ns[2]	3	60	160	1189	~88	~90 (+2)					1	Fløistad et al. (2007)
Ns[1,2]	3	56–57	180–250	1329	82[2] 34[1]			95[2] (+13) 80[1] (+46)			4	Örlander and Nilsson (1999)
Ns[1,2]	3	56–57	150	1384	~95[2] ~12[1]		~95[2] (±0) ~70[1] (+58)				4	Petersson and Örlander (2003)
Ns[2]	3	57	155	1349	41*[2] 12*[1]		**67[2]** (+26) **35[1]** (+23)	**65[2]** (+24) **26[1]** (+14)	68[2] (+27) 44[1] (+32)		1	Petersson (2011)
Ns[2]	3	57	170–240	1308	~80[2] ~44[1]		~95[2] (+15) ~89[1] (+45)				3	Härlin and Eriksson (2014, 2016), Eriksson et al. (2017)
Ns[2]	3	62–63	~140	1165	70			96 (+26)	95 (+25)		2	Heiskanen et al. (2013)
Ns[2]	4	61	400	861	~77*	**~84** (+7)					6	Kohmann (1999)
Ns[2]	4	56–58	150	1354	~73*		~90 (+17)		~97 (+24)		4	Bergquist et al. (2009)
Ns[1]	4	62	~140	1165	~72		73	93			1	Luoranen et al. (2006)
Ns[1]	5–6	59–61	80–450	947		~82 (+10)					3	Hine (1988)
Ns[2]	6	60–61	430–620	853	~86*	~90 (+4)			~93 (+7)		8	Granhus et al. (2003)
Ns[2]	7	56–57	130–190	1375	75*			88 (+13)	94 (+19)		2	Hjelm, pers. comm. (2019)
Ns[1,2]	7	57–58	200	1282	~65[2] ~16[1]		~87[2] (+22) ~60[1] (+44)				2 1	Thorsén et al. (2001)
Ns[1]	7	62	~140	1060	74		74[4]	87[4]			1	Uotila et al. (2010)
Ns[1]	8	65	480	467				89 (+15)			1	Bergan (1990)
Ns[2]	10	64	275–310	812	70*		95 (+25)	**96** (+26)	**98** (+28)	**100** (+30)	1	Örlander et al. (1998)
Ns[1]	10	56–57	170–180	1363		69				99	2	Örlander et al. (2002)
Ns[1]	12	61	50	1121	~81*	**~95** (+14)					1	Hine (1988)
Ns[2]	18	63–65	330–580	683	57			70 (+13)	80 (+23)		8	Johansson et al. (2013a)
Ns[2]	18	57	180–250	1287	58			71 (+13)	79 (+21)		2	Johansson et al. (2013a)

Table 1 continued.

Tree species	Years after planting	Latitude (°N)	Altitude (m a.s.l.)	Temp. sum (d.d. °C)	Survival (%) by MSP-method						No. of sites	Reference
					No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing		
Experiments												
Sp[1,2]	3	57	170–240	1308	~56[2] ~27[1]		~84[2] (+28) ~84[1] (+57)				3	Härlin and Eriksson (2014, 2016)
Sp[2]	4	56–58	150	1354	~70*		**~85** (+15)		~90 (+20)		4	Bergquist et al. (2009)
Sp[1]	4	66	200	855				90			1	Luoranen and Rikala (2013)
Sp[2]	5	62	130	1165			81	91			1	Luoranen and Rikala (2013)
Sp[2]	5	60	150	1172	70*		**96** (+26)				1	Johansson et al. (2013b)
Sp[2]	5	57	200	1312	63*		**90** (+27)				1	Johansson et al. (2013b)
Sp[1]	10	57	180	1329		93				95	1	Örlander et al. (2002)
Sp[3]	18	67	440	507	~16*	**~34** (+18)		**~49** (+33)			1	Hansson and Karlman (1997)
Sp[3]	25–27	66–68	180–290	783		45	42			58	8	Mäkitalo et al. (2010)
Lp[1]	5	64	150	913		99				99	1	Örlander et al. (2002)
Lp[2]	10	64	275–310	812	72*		**86** (+14)	**90** (+18)	**98** (+26)	**98** (+26)	1	Örlander et al. (1998)
Lp[1,2]	17	62	370–420	847	89		95 (+6)	95 (+6)		95 (+6)	3	Mattson and Bergsten (2003)
Lp[3]	18	67	440	507	~44*	~50 (+6)		**~60** (+16)			1	Hansson and Karlman (1997)
Surveys												
Ns[2]	3	60–64	20–300	–	76	84 (+8)	83 (+7)	91 (+15)			5196	Saksa and Kankaanhuhta (2007)
Ns[1]	4	61–63	90–140	–			85	93			3	Luoranen et al. (2006)
Ns[3]	4	62	~140	–		93	81	93			24	Saksa (2011)
Ns[3]	10	62–67	–	–			74	74			23	Söderbäck (2012)
Sp[2]	3	60–64	20–300	–	47	73 (+26)	82 (+35)	87 (+40)			1951	Saksa and Kankaanhuhta (2007)
Sp[3]	10	62–67	–	–			76	76			31	Söderbäck (2012)
Lp[3]	10	62–67	–	–				86			5	Söderbäck (2012)

[1] Seedlings not treated with an insecticide.
[2] Seedlings treated with an insecticide.
[3] No information given about whether seedlings were treated with an insecticide. Seedlings were probably not treated.
[4] Estimated mortality.

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Table 2. Mean heights (cm) of planted Norway spruce (Ns), Scots pine (Sp) and Lodgepole pine (Lp) seedlings following each mechanical site preparation method (MSP) and No MSP, in field experiments and survey studies obtained 3–27 growing seasons after planting. The character ~ indicates values estimated from a diagram and * in "No MSP" that statistical analysis was reported in that study. Bold values indicate a statistically significant difference from the control ("No MSP") and values in brackets show differences in percentage relative to "No MSP". In most experiments, the planted seedlings were protected by an insecticide to reduce pine weevil (*Hylobius abietis* L.) damage. In the experiments where both protected and unprotected seedlings were planted values are shown for both types.

Tree species	Years after planting	Latitude (°N)	Altitude (m a.s.l.)	Temp. sum (d.d. °C)	Height (cm) by MSP-method						No. of sites	Reference
					No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing		
Experiments												
Ns[2]	3	60	200	1116	34*	46 (+35)		46 (+35)			1	Brække et al. (1986)
Ns[2]	3	60	160	1189	~40	~48 (+20)					1	Fløistad et al. (2007)
Ns[1,2]	3	56–57	150	1384	~57[2] / ~36[1]		~62[2] (+9) / ~51[1] (+42)				4	Petersson and Örlander (2003)
Ns[2]	3	62–63	~140	1165	46			48 (+4)	46 (±0)		2	Heiskanen et al. (2013)
Ns[2]	5	56–57	180–250	1329	117			126 (+8)			4	Nilsson and Örlander (1999b)
Ns[1]	5–6	59–61	80–450	947	~60	~64 (+7)					3	Hine (1988)
Ns[2]	6	60–61	430–620	853	~58*	~66 (+14)					8	Granhus et al. (2003)
Ns[2]	7	56–57	130–190	1375	146*			**166** (+14)	~72 (+24)		2	Hjelm, pers. comm. (2017)
Ns[2]	7	57–58	200	1282	~150[1] / ~130[2]		~170[1] (+13) / ~150[2] (+15)		**179** (+23)		2	Thorsén et al. (2001)
Ns[1]	7	62	~140	1060			68	110			1	Uotila et al. (2010)
Ns[1]	8	65	480	467	34			51 (+50)			1	Bergan (1990)
Ns[2]	10	64	275–310	814	~80*		~145 (+81)	~140 (+75)	~210 (+162)	~165 (+106)	1	Örlander et al. (1998)
Ns[1]	10	56–57	170–180	1363		~150				~270	2	Örlander et al. (2002)
Ns[1]	12	61	50	1121	~82*	~117 (+43)					1	Hine (1988)
Ns[2]	18	64.5	410	683	230			324 (+41)	320 (+39)		8	Johansson et al. (2013a)
Ns[2]	18	57	215	1287	822			830 (+1)	789 (–4)		2	Johansson et al. (2013a)
Sp[2]	5	60	150	1172	88*		113 (+28)				1	Johansson et al. (2013b)
Sp[2]	5	57	200	1312	111*		138 (+24)				1	Johansson et al. (2013b)
Sp[1]	10	56–57	170–180	1329		~345				~395	1	Örlander et al. (2002)
Sp[3]	18	67	440	507	242*	267 (+10)		**303** (+25)			1	Hansson and Karlman (1997)
Sp[3]	25–27	66–68	180–290	783	591	591	574			613	8	Mäkitalo et al. (2010)

Table 2 continued.

Tree species	Years after planting	Latitude (°N)	Altitude (m a.s.l.)	Temp. sum (d.d. °C)	No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing	No. of sites	Reference
Experiments												
Lp[2]	10	64	275–310	814	~200*		~**265** (+32)	~**250** (+25)	~**320** (+60)	~**280** (+40)	1	Örlander et al. (1998)
Lp[1]	10	56–57	170–180	1363		~205				~370	1	Örlander et al. (2002)
Lp[1,2]	17	62	370–420	847	320		410 (+28)	430 (+34)		510 (+59)	3	Mattson and Bergsten (2003)
Lp[3]	18	67	440	507	258*	**328** (+27)		**360** (+40)			1	Hansson and Karlman (1997)
Surveys												
Ns[2]	3	60–64	20–300	–		53	52	56			1591	Saksa and Kankaanhuhta (2007)
Ns[1]	4	61–63	90–140	–			33	46			2	Luoranen et al. (2006)
Ns[3]	4	62	~140	–		66	64	71			24	Saksa (2011)
Ns[3]	9	61–63	90–140	–			166	215			22	Saksa et al. (2005)
Ns[3]	10	62–67	–	–			196	196			23	Söderbäck (2012)
Sp[3]	10	62–67	–	–			247	247			31	Söderbäck (2012)
Lp[3]	10	62–67	–	–				286			5	Söderbäck (2012)

[1] Seedlings not treated with an insecticide.
[2] Seedlings treated with an insecticide.
[3] No information given about whether seedlings were treated with an insecticide. Seedlings were probably not treated.

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Meteorological Institute (Venäläinen et al. 2005). In all cases, temperature sums were expressed as degree days (d.d. °C) with a threshold temperature of 5 °C.

The Norway spruce, Scots pine and lodgepole pine experiments were located between latitude 56 and 65 °N, 56–68 °N and 62–67 °N, respectively, while all surveys were conducted at latitudes 60–67 °N (Tables 1 and 2). The sites represented are typically mesic (as well as some dry or moist) with mineral soils, mainly sandy-silty moraines (also some sediments). The yield capacity for the sites with Norway spruce varied between ca. 2 and 12 m^3 ha^{-1} yr^{-1} (site index$_{H100}$ 16–32 m; tree dominant height at age 100 years) and with Scots pine ca. 2–8 m^3 ha^{-1} yr^{-1} (site index$_{H100}$ 17–28 m), site index here according to the Swedish system (Hägglund and Lundmark 1982). For the sites with lodgepole pine, no yield capacities specific for this species were given, but in some studies yields were instead reported for Scots pine at the same site, i.e. site indices$_{H100}$ of 14–16 m corresponding to ca. 2–5 m^3 ha^{-1} yr^{-1}. The seedlings planted were almost always container-ized, but in a few cases bareroot or hybrid seedlings (a combination of container and bareroot) were used. In seven of the experimental studies the seed source was seed orchards and in five it was forest stands ("local site" or "suitable provenance"). Moreover, in 13 studies, the provenance was given without specifying genetic improvement and nine had no specification at all. However, since the same seed source was used in each single experiment the seed origin probably has no or minor influence on the MSP-effect for either seedling survival or growth. The descriptions above are based on available data given in the references in Tables 1–2.

3.2.1 Survival and tree height

Generally, mean survival rates and tree heights associated with each treatment are presented in the germane studies. It is well known that pine weevil causes severe damage and mortality of planted conifer seedlings in clearcuts in the region covered in this review (Nordlander et al. 2011), especially in the more southerly area. It is also well established that both mechanical protection and chemical substances reduce pine weevil damage and mortality (Pettersson and Örlander 2003). Therefore, special attention was paid to whether the seedlings in the cited studies were protected from pine weevils. Where possible, data pertaining to results of different MSP methods for protected and non-protected seedlings were considered separately.

Another reason for presenting sub-group mean values of published data in our compilation was when the experimental sites were far apart. Johansson et al. (2013a) presented mean data for 10 sites (eight in northern Sweden and two in southern Sweden), and separate means for the northern and southern sites were provided by Karin Hjelm (pers. comm. 2019). The regional means were used in our statistical analyses (see below). Luoranen and Rikala (2013) monitored two sites, in central and northern Finland, and results are presented separately for these two regions.

Analyses were conducted on two data sets: 1) with all 34 observations from field experiments listed in Tables 1–2 (ALL DATA), and 2) with those including a No MSP control treatment (NO MSP DATA), which included 26 and 20 experiments for survival and height, respectively. MSP-effects (differences in results between each MSP method and No MSP) were derived from the latter. MSP-effects for survival rates and tree heights are presented as differences in percentage units (p.u.), and percentages, respectively.

3.2.2 Statistical analyses

The compiled data from the field experiments on survival rates, tree heights and annual height growth were analysed using analysis of variance (ANOVA) including NO MSP DATA, and, for survival, ALL DATA was also analysed. In addition, MSP-effects on survival and tree heights were

evaluated (based on NO MSP DATA). The MIXED procedure of the SAS program version 9.4 (SAS Institute, Cary, NC, USA) was used to analyse models of the form (all five MSP-methods merged in Eq. 1 and analysed separately in Eq. 2):

$$y_{ik} = \mu + s_i + msp_k + b_1\left(Ts_i - \overline{Ts}\right) + b_2\left(T_i - \overline{T}\right) + e_{ik} \tag{1}$$

$$y_{ijk} = \mu + s_i + t_j + msp_k + b_1\left(Ts_i - \overline{Ts}\right) + b_2\left(T_i - \overline{T}\right) + e_{ijk} \tag{2}$$

where μ = the overall mean; s_i = the random effect of site, i = 1–19 (height and annual height growth), 1–25 (survival NO MSP DATA) or 1–33 (survival ALL DATA), IND $(0, \sigma_b^2)$; t_j = the fixed effect of tree species, j = 1, 2, 3; msp_k = the fixed effect of MSP-method (merged or separate), k = 1–6, 1–5 or 1–2; b_1 = regression of y_{ijk} over temperature sum; Ts = temperature sum for site$_i$; b_2 = regression of y_{ijk} over time since planting; T = time since planting for site$_i$; e_{ijk} = the random error, IND $(0, \sigma_e^2)$.

In all the analyses of survival, tree height and annual height growth, the covariates temperature sum and years since planting were tested in the models, both individually and together, to determine their influence on survival rates, tree heights, annual height growth and MSP-effects (survival and tree height).

The collated data from the field experiments on survival rates and MSP-effects on survival and tree height were also plotted against temperature sum and number of years since planting. In addition, the relationships between the two MSP-effects (survival and tree height) (y) and both temperature sum (Ts) and number of years since planting (T) were estimated in meta analyses by linear regression. The REG procedure of the SAS program version 9.4 (SAS Institute, Cary, NC, USA) was used for the calculations. The following models were tested for both survival and tree height:

$$y = k + a \times Ts \tag{3}$$

$$y = k + a \times Ts + b \times Ts^2 \tag{4}$$

$$y = k + a \times T \tag{5}$$

$$y = k + a \times T + b \times T^2 \tag{6}$$

In these equations, k is the intercept, and a and b are coefficients. For the curvilinear relationships, the optimum was determined by looking at the fit of the model and testing different "x-values" to find the maximum for the equation.

The effect on survival of insecticide treatment targeting pine weevil, based on the six studies that included both treated and untreated seedlings (Table 1), was analysed in the following model:

$$y_{ijk} = \mu + s_i + t_j + msp_k + pw_l + msp_k \times pw_l + e_{ijk} \tag{7}$$

where: i = 1–6, IND $(0, \sigma_b^2)$; j = 1, 2; k = 1–4; pw_l = pine weevil treatment, l = 0, 1 (see also Eq. 2).

In all analyses, an individual observation was weighted according to the number of sites (experiments) representing the observation (one study). Differences between the class means for tree species and MSP-method were evaluated using Tukey´s significant differences (HSD) mean separation test.

4   Results

4.1 Survival

4.1.1 Data based on experiments

The survival rate for MSP (all five MSP-methods merged) was 15 p.u. greater than No MSP according to the ANOVA for ALL DATA (83% ± 2.1 vs. 68 ± 2.3%; p < 0.001) and 14 p.u. greater for NO MSP DATA (84% ± 2.6% vs. 68% ± 2.7%; p < 0.001). In both analyses, time after planting was included in the model as a covariate (p < 0.001 and p = 0.006, respectively).

There was generally a greater survival rate for all five individual MSP methods by 11–24 p.u. compared with No MSP according to the ANOVA (p < 0.001; ALL DATA; Table 3). In addition, soil inversion resulted in 8 p.u. higher survival rate than patch scarification, and ploughing 13 p.u. and 11 p.u. higher rates, respectively, than patch scarification and disc trenching. The mean effect periods after planting were 7–13 years for the different MSP-methods. In these analyses of the absolute survival rates, there were no statistically significant differences between tree species (Table 3). The treatment effects were similar when NO MSP DATA were analysed, except for ploughing, which exhibited a 7 p.u. smaller MSP effect (Table 3).

The ANOVA of the MSP-effects on survival showed least-square means 14–21 p.u. greater for the tested methods 6–12 years after planting (based on NO MSP DATA). Soil inversion gave a 5–7 p.u. greater effect than patch scarification, disc trenching and mounding (p < 0.002; Table 3). There was a greater general MSP-effect for Scots pine than for lodgepole pine (+14 p.u.; p < 0.05), and a tendency for a greater effect on Scots pine than Norway spruce (+9 p.u.; p = 0.059).

The observed survival rates for all tree species following all five MSP methods (excluding No MSP) 3–26 years after planting (mainly of containerized seedlings) ranged from 34 to 100% in the studies (ALL DATA), which covered temperature sums between about 500 and 1400 degree days °C (d.d. °C) (Fig. 2). The overall survival rates were between 65% and 100% at temperature sums above 800 d.d. °C. Below 800 d.d. °C, the survival rates were more variable, in the range 34–90%.

There was no clear relationship between the size of the MSPs' effects on survival and either temperature sum (p = 0.57) or number of years after planting (p = 0.37) (Fig. 3).

In eleven of the 14 studies reporting statistical analysis on treatment effects of MSP for the survival data reported in Table 1, all the tested MSP-methods resulted in significantly greater survival rates than No MSP. In one study, soil inversion and disc trenching resulted in higher survival rates for Norway spruce, but mounding did not (seedlings not protected with insecticides (Petersson 2011)). In another study, soil inversion was superior to No MSP, but patch scarification was not (Norway spruce; Granhus et al. 2003). In the last exception, mounding was superior to No MSP, but patch scarification was not (Lodgepole pine; Hansson and Karlman 1997).

4.1.2 Data based on surveys

In the only survey of Norway spruce that included sites subjected to No MSP (Saksa and Kankaanhuhta 2007), mean survival rates were 7–8 p.u. higher at sites subjected to patch scarification or disc trenching and 15 p.u. higher in mounded sites compared with No MSP sites (Table 1). Mean survival rates following these three MSP methods recorded in all four survey studies were similar: 88% (n = 2), 81% (n = 4) and 88% (n = 4), respectively. The two Finnish surveys (one very large) conducted 3–4 years after planting found that mounding resulted in 8 and 12 p.u. higher average survival than disc trenching (Table 1; Saksa and Kankaanhuhta 2007; Saksa 2011). No such difference was detected in the survey of Swedish stands by Söderbäck (2012), who found survival rates were the same (74%) following both disc trenching and mounding 10 years after planting.

Table 3. ANOVA results for the effects of mechanical site preparation method (MSP method; least-square means (lsmeans) ± stderr) of plan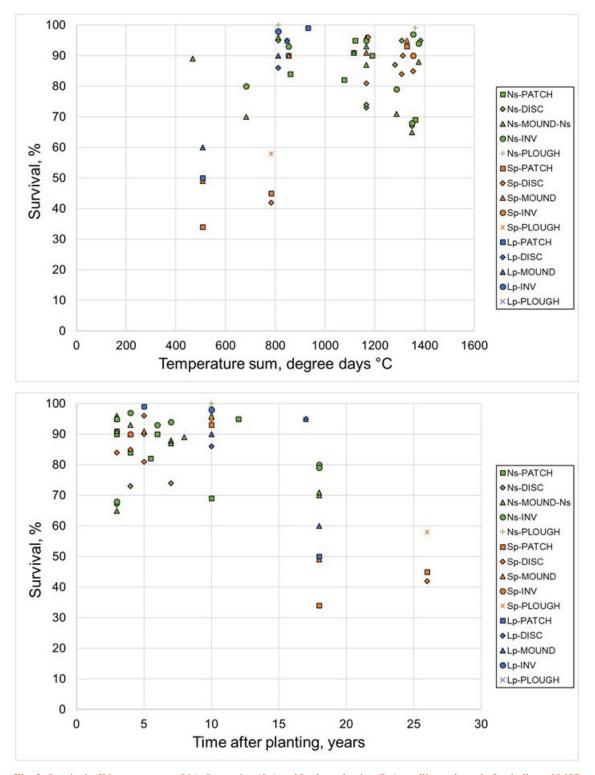ted Norway spruce, Scots pine and lodgepole pine seedlings following each MSP method in field experiments. Survival (%) refers to analyses of the survival of all MSP treatments, as well as of the MSP-effects, i.e. the difference in percentage units between results of the MSP methods and no site preparation (No MSP). For height, both the absolute tree heights (cm) in all treatments and the relative MSP-effects are given. The relative MSP-effect on height and annual height growth refers to the difference in percentage (%) between results of the MSP methods and No MSP. Data obtained 3–27 growing seasons after planting. Values with different letters in the same row indicate statistically significant differences (p<0.05) for tree species and MSP-method, respectively. NO MSP DATA = studies including a control treatment without MSP.

Data	p-value				Lsmeans, tree species				Lsmeans, MSP-method				
	Site	Tree species	MSP method	Residual	Norway spruce	Scots pine	Lodgepole pine	No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing
Survival													
ALL DATA[1] (n=88)	0.001	0.12	<0.001	<0.001	84±2.3 a	76±3.7 a	86±4.2 a	68±2.3 a	79±2.7 b	81±2.6 bc	84±2.7 bcd	87±2.7 cd	92±3.2 d
NO MSP DATA[2] (n=72)	0.002	0.070	<0.001	<0.001	85±2.7 a	71±5.2 a	84±4.6 a	68±2.7 a	77±3.3 b	83±3.0 bc	82±3.1 bc	86±3.0 c	85±4.8 bc
MSP-effect (n=46)	0.002	0.015	0.002	0.001	16±1.7 ab	25±3.4 b	11±3.0 a	–	14±2.3 a	16±2.0 a	16±2.0 a	21±2.0 b	19±3.0 ab
Height													
NO MSP DATA[3] (n=56)	0.005	0.001	<0.001	<0.001	193±25 a	195±57 ab	298±32 b	187±26a	208±28 ab	215±29 ab	235±27 bc	233±27 bc	295±33 c
MSP-effect[4] (n=36)	0.14	0.12	0.27	0.015	38±6.7 a	26±16 a	10±11 a	–	11±10 a	23±10 a	20±8.6 a	24±9.5 a	46±14 a
Annual height growth													
NO MSP DATA[5] (n=56)	0.007	<0.001	<0.001	<0.001	17±1.4 a	21±3.1 a	28±1.9 b	19±1.4 a	21±1.6 ab	22±1.6 b	23±1.5 bc	23±1.5 bc	26±1.9 c

[1] Number of years after planting (p = <0.001) was included in the statistical model as a covariate.
[2] Number of years after planting (p = 0.003) was included in the statistical model as a covariate.
[3] Temperature sum (p = 0.001) and number of years after planting (p = <0.001) were included in the statistical model as covariates.
[4] Temperature sum (p = 0.020) was included in the statistical model as a covariate.
[5] Temperature sum (p = <0.001) and number of years after planting (p = 0.001) were included in the statistical model as covariates.

Fig. 2. Survival of Norway spruce (Ns), Scots pine (Sp) and Lodgepole pine (Lp) seedlings planted after indicated MSP methods (PATCH = patch scarification, DISC = disc trenching, MOUND = mounding, INV = soil inversion, PLOUGH = ploughing) as functions of temperature sum (degree days °C; threshold 5 °C) at locations of the studies (upper panel), and time after planting (lower panel). Data from all experimental studies summarized in Table 1 (ALL DATA; n = 62), each of which included observations at 1–10 experimental sites.

Fig. 3. Effects on survival of indicated mechanical site preparation methods (MSP effects, i.e. differences between each method and no MSP: PATCH = patch scarification, DISC = disc trenching, MOUND = mounding, INV = soil inversion, PLOUGH = ploughing) of subsequently planted Norway spruce (Ns), Scots pine (Sp) and lodgepole pine (Lp) seedlings as functions of temperature sum (Ts; degree days °C, threshold 5 °C) at locations of the studies (upper panel), and time after planting (T) (lower panel). Data from studies presenting experimental data summarized in Table 1 including No MSP treatment (NO MSP DATA; n = 46), each of which included observations at 1–10 experimental sites.
Trend = $15.5 + 0.002 \times Ts$; $R^2 = 0.01$; $p = 0.57$ (upper panel).
Trend = $19.7 – 0.199 \times T$; $R^2 = 0.02$; $p = 0.37$ (lower panel).

In the Finnish survey of Scots pine that included sites subjected to No MSP, the survival rates were 26 p.u. higher on average following patch scarification and 35–40 p.u. higher following disc trenching or mounding (Table 1; Saksa and Kankaanhuhta 2007); 12 and 19–24 p.u, respectively, higher than the mean MSP-effects shown in the experimental data for these methods (cf. Table 3). The survival rates following disc trenching and mounding recorded in the Swedish survey (76%) were 6 and 11 p.u. lower, respectively, than those recorded in the Finnish survey. However, they were recorded, on average, 10 years after planting in the Swedish survey, seven years later than in the Finnish survey (Table 1).

The single survey of lodgepole pine stands showed a similar mean survival rate following disc trenching (86%, 10 years after planting on average; Table 1) to the corresponding rate observed in the experimental tests of this MSP method (Table 3).

4.1.3 Treatment against pine weevil

Treatments that controlled pine weevil exhibited statistically significant effects of MSP method ($p < 0.001$), pine weevil treatment ($p = 0.002$) and the interaction between MSP method and pine weevil treatment ($p = 0.016$), but not site ($p = 0.12$) or tree species ($p = 0.96$) (Fig. 4). Treated seedlings had an overall survival rate of $83\% \pm 10\%$ (lsmean $\pm$ stderr) and non-treated ones $56\% \pm 10\%$, i.e. a treatment effect of +27 p.u. 3–7 years after planting. When planted after No MSP, treated seedlings had 50 p.u. significantly ($p < 0.001$) higher survival rate than non-treated ones (Fig. 4). For each MSP-method, the corresponding differences in survival rate (not significant in any cases) were +16 p.u. (disc trenching), +20 p.u. (mounding) and +24 p.u. (soil inversion). On average for the three tested MSP-methods, treated seedlings showed a 20 p.u. higher survival rate than non-treated ones.
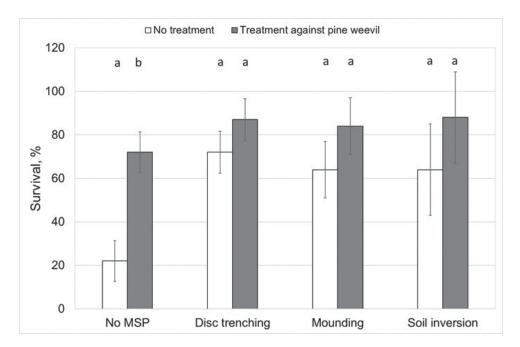

Fig. 4. Survival of Norway spruce (Ns) and Scots pine (Sp) seedlings, without and with chemical treatment against pine weevil (*Hylobius abietis* L.), planted after indicated mechanical site preparation (MSP) methods. Lsmeans $\pm$ standard error. Data from six experimental studies in Table 1 (five Ns and one Sp; n = 28), each of which included observations at 1–4 experimental sites. Values with different letters within MSP method indicate statistically significant differences ($p < 0.05$) for pine weevil treatment.

4.2 Tree height

4.2.1 Data based on experiments

For all five MSP-methods merged, the mean tree height for MSP was 24% greater than No MSP according to the ANOVA for the NO MSP DATA (209 ± 21 cm vs. 168 ± 22 cm; $p < 0.001$) and the annual height growth was 25% greater (20 ± 1.2 cm vs. 16 ± 1.2 cm; $p < 0.001$). In both analyses, temperature sum and time after planting were included in the model as covariates ($p < 0.001$ for all).

The mean tree heights after mounding, soil inversion and ploughing were greater compared with No MSP according to the ANOVA ($p < 0.001$; NO MSP DATA; Table 3). In addition, ploughing produced taller trees than patch scarification and disc trenching. The mean effect periods after planting were 8–12 years for the different MSP-methods in the studies included. In this analysis, the mean height in the lodgepole pine experiments was significantly higher than in the ones with Scots pine (Table 3). The analysis of annual height growth showed similar differences among both tree species and MSP-methods as the analysis of tree height (Table 3).

The MSP-effect on tree height (height increase relative to No MSP controls) was between 10% and 38% on average, depending on tree species, and between 11% and 46% among the five MSP methods according to the ANOVA (based on NO MSP DATA; Table 3). The mean times after planting were between 8 and 12 years in the different treatments, and there were no statistically significant differences among either tree species or MSP methods. The MSP-effects on mean height varied between –4% and +60% in the individual studies, except for the study by Örlander et al. (1998), which reported improved Norway spruce seedling growth of 75–162% (Fig. 5).

The MSP-effects on tree height tended to decrease with increases in temperature sum in the interval from about 500 to 1400 d.d. °C when all data were included (curvilinear relationship, $p_{model} = 0.008$) (Fig. 5). Moreover, the MSP-effect on tree height showed a curvilinear relationship with number of years after planting ($p_{model} = 0.002$), being strongest 11.4 years after planting (Fig. 5).

In six of the nine studies reporting statistical analysis of the treatment effects of MSP for the tree height data reported in Table 2, all the tested MSP-methods resulted in significantly greater heights than No MSP. In one other study, neither of the methods tested (patch scarification and mounding) were associated with taller Norway spruce (Brække 1986). In the two other exceptions, soil inversion (Norway spruce; Granhus et al. 2003) and mounding (Scots pine; Hansson and Karlman 1997) were superior to patch scarification. Only in the study by Örlander et al. (1998) was a single MSP-method (inversion, both for Norway spruce and Lodgepole pine) significantly superior to the other three methods tested.

4.2.2 Data based on surveys

None of the surveys compared tree height after MSP to No MSP. In the two surveys of Norway spruce including sites subjected to disc trenching, mounding and patch scarification, the mean heights of the seedlings were respectively 2% lower and 7% higher, on average, following disc trenching and mounding than following patch scarification (Table 2). On average, according to data in all five surveys, mounding resulted in 18% greater mean tree height than disc trenching (Table 2). The Swedish survey found that the mean height of Scots pine seedlings was the same following both disc trenching and mounding 10 years after planting (Table 2; Söderbäck 2012). The mean height of the lodgepole pine trees was 286 cm ten years after mounding and planting in the five stands surveyed in Sweden (Table 2).
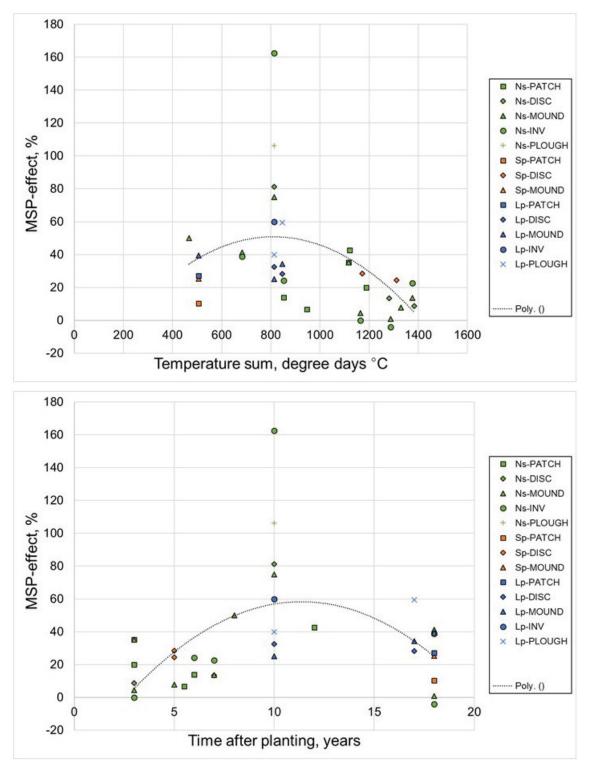
Fig. 5. Effects on height of indicated mechanical site preparation methods (MSP effects: PATCH = patch scarification, DISC = disc trenching, MOUND = mounding, INV = soil inversion, PLOUGH = ploughing) of planted Norway spruce (Ns), Scots pine (Sp) and lodgepole pine (Lp) seedlings as functions of temperature sum (upper panel) and time after planting (lower panel). Data from the studies presenting experimental data summarized in Table 2 including No MSP treatment (NO MSP DATA; n = 36), each of which included observations at 1–10 experimental sites. For further explanations, see Fig. 3.
Poly = –41.2 + 0.227 × Ts – 0.00014 × Ts^2; R^2 = 0.25; p$_{model}$ = 0.008 (upper panel).
Poly = –39.4 + 17.2 × T – 0.757 × T^2; R^2 = 0.30; p$_{model}$ = 0.003 (lower panel).

4.3 Disturbed soil surface area

According to the collated data, mounding affected 37% of the surface area of treated sites, on average (range: 17–67% at individual studied sites, Table 4). Corresponding proportions for disc trenching and ploughing were 52% (33–70%), and 62% (53–69%), respectively. The proportions for patch scarification and soil inversion, in each case reported in only one study, were 49 and 51%, respectively.

4.4 Natural regeneration densities

In four of the five studies including a No MSP control treatment, densities of naturally regenerated seedlings were higher following the MSP-treatments than following No MSP (Table 5). Ranges of recorded densities following MSP and No MSP were 2000 to 19 000 seedlings ha^{-1} and 1000 to 8000 seedlings ha^{-1}, respectively. In the chronosequence survey by Lehtosalo et al. (2010), the densities of naturally regenerated seedlings were similar following No MPS, mounding and disc

Table 4. Disturbed soil surface area (%) following each mechanical site preparation method (MSP) and No MSP.

No MSP	Patch scarification	Disc trenching	Mounding	Soil inversion	Ploughing	Reference
	49	50			60	Pohtila and Pohjola (1985)[1]
		54	35		69	Bäcke et al. (1986)[2]
			20–30			Adelsköld (1986)[3]
		40–47			53–58	Saksa (1987)[4]
		70	30			von Hofsten (1989)[5]
			52–67			von Hofsten (1991)[6]
9			50			Karlsson et al. (2002)[7]
			35			von Hofsten and Nordén (2002)[8]
		61				Nilsson et al. (2002)[9]
14			55	51		Hallsby and Örlander (2004)[10]
			17–19			Lehtosalo et al. (2010)[11]
		33	22			Sjögren (2013)[12]

[1] A study in N Finland including eight experiments, four established in former Scots pine-dominated forest and four in former Norway spruce-dominated forest. Split-plot experiments, four site preparation methods (patch created by a scarifier; disc trenching by a TTS–35 disc trencher; ploughing by a ridge plough or a shoulder-plough). The disturbed soil surface area was measured in a circular plot (200 m^2) within each treatment plot (12 000 m^2) and values presented are means per MSP-treatment.

[2] Means for five sites in Northern Sweden, inventoried along parallel lines. Mounding was done with an aggregate from Bracke (Bräcke mounder; at least 10 l soil placed on upturned humus) and disc trenching with a "Murveln disc trencher" manufactured by Järvsö Skogsmekan, and ploughing with Marttini and Lönntek ploughs. See also Mattsson and Bergsten (2003).

[3] Site preparation in different terrains. Two types of mounding equipment were used: Bracke and Donhög 190, which affected 20–25% and 25–30% of the surface area, respectively, in both cases with 2 m spacing between rows.

[4] Practical reforestation areas with disc trenching done by TTS-disc trenchers and ploughing, mainly by shoulder-ploughs. The disturbed soil surface area was measured in ca. 50 circular plots per plantation, the plots 6 m^2 or 10 m^2 depending on the density of the plantation. Values presented are means of the monitored regeneration areas per MSP-method.

[5] A Donaren 230 MIDAS disc trencher was used both continuously (disc trenching) and patch wise (mounding).

[6] Three different site types were evaluated, following use of a Bracke aggregate creating both long patches ending with a mound (n = 1), and large mounds (n = 2). The distance between the rows with mounds was ca. 2 m. The disturbed area was calculated as the total distance monitored, minus the unaffected distance between the mounds, multiplied by the mean width of the mounds.

[7] Mounding was performed using an excavator at four sites in southern Sweden. The mounds were made of 20 dm^3 mineral soil and were 10–20 cm high. Presented data are means for four sites, min–max, control 4–17% and mound 41–55%.

[8] A combined site preparation aggregate (GSSP97) that could be used either for mounding (the data presented here) or patch scarification was used.

[9] In this study, 8% was recorded as pure mineral soil and 53% as berm, after disc trenching.

[10] Site preparation completed with an excavator. The site prepared spots had areas of ca. 0.5 m^2 and a 0.1–0.2 m deep layer of mineral soil covered the buried humus. Mound spacing ca. 2 m. The total area of disturbed soil surface is given. With soil inversion, there was less variation in occurrence of altered surface contours than with mounding. Average for 12 sites.

[11] 9–10% of the surface area recorded as "mounds" and 8–9% as "patches". Means for 18 monitored sites.

[12] Disc trenching equipment not specified. Mounding was done with a Bracke Planter. Three sites per method were monitored.

Table 5. Number of naturally regenerated seedlings (mainly birch) per hectare following each mechanical site preparation method (MSP; i.e. disc trenching, mounding, soil inversion and patch scarification) and No MSP. The total area column presents densities in the whole regeneration areas, both affected and not affected by MSP. The affected area column presents densities for different MSP methods only in the area disturbed by the MSP. Data from field experiments and surveys of stands established in operational forestry, recorded 3–14 growing seasons after planting.

Tree species	Years after planting	Total area				Affected area				No. of sites	Location, Reference
		No MSP	Disc trenching	Mounding	Inverting or Patch scarification	No MSP	Disc trenching	Mounding	Inverting or Patch scarification		
Birch	3			4700–15100		~4500–~16000		~4000–~12000	~9500–~10000	18	Southern Finland Lehtosalo et al. (2010)[1]
Birch	5	~5000	~6000				13 900 (furrow) 2900 (berm)			1	Southern Sweden Nilsson et al. (2002)[2]
Birch	5	3000		19400						4	Southern Sweden Karlsson et al. (2002)[3]
All species	5		12000–19000		5000–15000					2	Southern Sweden Holmström et al. (2016)[4]
Birch	5–8	14400	6100							8	Southern Sweden Karlsson and Nilsson (2005)[5]
Birch	6			8500–16100		~6000–~13000		~20000–~35000	~14500–~23000	18	Southern Finland Lehtosalo et al. (2010)[1]
All species	7		22570	14490						1	Central Finland Uotila et al. (2010)[6]
Broad-leaves	5–8	~2500–~8000	~4000–~14000							22	Southern Sweden Nilsson et al. (2006)[7]
Birch	9			6800–9600		~4000–~6000		~25000–~28000	~10500–~17500	18	Southern Finland Lehtosalo et al. (2010)[1]
All species	14	921		2151	2136					10	Sweden Johansson et al. (2013a)[8]

[1] Survey study (chronosequence) of clearcuts of different ages (three, six and nine years after mounding and planting) of Norway spruce seedlings. In total 18 sites in Finland (Lat 60.5–62°N), nine of *Myrtillus* and nine of *Oxalis-Myrtillus* vegetation types.
[2] One trial at Tönnersjöheden (56°40′N); dry to mesic soil; coarse/sandy texture and sandy-silty till; site index for spruce 30 m (upper height at 100 years).
[3] Four sites close to Tönnersjöheden (56°20′N) and Asa (57°08′N); fertile soils. At Asa mesic moist sandy till, site index for spruce 28 m. At Tönnersjöheden dry till with coarse texture, site index 31 m for spruce.
[4] Two sites in southern Sweden; Kronoberg and Halland, four blocks in Kronoberg with disc trenching or inverting and three blocks in Halland with disc trenching or no site preparation.
[5] Eight sites in southern Sweden; three with patch scarification and five with disc trenching; seven mesic sites, *Vaccinium myrtillus* and one dry, *Carex* ssp. vegetation types. Site indices for pine, 22–26 m.
[6] One site in central Finland (Suonenjoki). Number of stems removed during pre-commercial thinning.
[7] Twenty-two sites in Sweden – eight in northern, eight in central and six in southern Sweden (site indices, 20–24, 23–26 and 18–28 m, respectively). Mainly mesic soils and sandy-silty tills, but one dry site and two with silty clays. *Vaccinium* ssp. or *Carex* ssp. vegetation types.
[8] Ten sites in Sweden along north-south cline (lat. 57 to 65°N). Site indices 16–32 m. All naturally regenerated stems above 1.3 m in height included, mainly broadleaves.

trenching in three-year old clearcuts (4000–16 000 ha^{-1}), but 1–4 times higher following the two MSP-treatments than following No MSP in 6- and 9-year old clearcuts. In contrast, Karlsson and Nilsson (2005) found that the density was ca. twice as high without MSP as it was following disc trenching (Table 5).

5 Discussion

5.1 Influence of MSP on regeneration success

5.1.1 Survival

Our study shows that mechanical site preparation can lead to high survival rates (80–90%) of planted conifer seedlings on mineral soil sites in Fennoscandia; in general, 15–20 p.u. higher than rates recorded following planting at non-prepared sites (Table 3). Soil inversion and plough-ing (few studies) seemed to be associated with somewhat higher MSP-effects and survival rates than patch scarification, disc trenching and mounding. Weaker MSP-effects were also recorded in some of the few studies with lodgepole pine seedlings, but their survival rates were similar to those of Norway spruce and Scots pine seedlings. These conclusions are mainly based on the experimental data, especially the analysis of the MSP-effect, which is considered the most relevant analysis since MSP observations are compared with an untreated control (No MSP) at the same site. The recorded survival rates and MSP-effects in the surveys were mainly within the ranges above, except for somewhat lower survival rates (74–76%) for Norway spruce and Scots pine in the Swedish survey (Söderbäck 2012), greater MSP-effects for Scots pine amounting to 26–40 p.u. in the Finnish survey reported by Saksa and Kankaanhuhta (2007), and somewhat greater MSP-effects (7–12 p.u.) associated with mounding than disc trenching for Norway spruce in some of the Finnish surveys (Table 1).

Altered physical, chemical and biological conditions at forest sites that benefit planted coniferous seedlings in various ways may help to explain the positive effect on survival in our study. Reduction of water stress experienced by seedlings after MSP has been demonstrated on several occasions (Bjor 1971; Grossnickle and Heikurinen 1989; Fleming et al. 1994). However, the effect on soil moisture conditions is sometimes modest (Wetzel and Burgess 2001; Johansson et al. 2005), and each MSP method may have distinct effects on soil moisture. Mounding, for example, creates elevated planting spots that may be associated with enhanced soil drainage, which may be favourable at wet and cold sites but less so under dry and warm conditions (Bassman 1989; Sutton 1993; de Chantal et al. 2003; Löf et al. 2012).

Furthermore, exposing the mineral soil bare by removing the humus layer has been found to ameliorate temperature extremes that may occur in the top of the humus layer (Bjor 1971), but increase overall soil temperatures (McMinn 1985; Bassman 1989; Man and Lieffers 1999; Burgess and Wetzel 2000), thereby improving conditions for root growth and establishment. Site preparation also increases minimum air temperatures above the surface, and thus reduces the risk of frost damage (Brække 1972; Blennow 1998; Langvall et al. 2001). However, removal of the humus layer may increase diurnal variations in heat fluxes in the soil, which can increase frost heaving, especially in fine-textured silty soil (Söderström 1973; Bergsten et al. 2001; de Chantal et al. 2007). In the data examined here, the MSP-effect on survival seemed to be independent of the temperature sum (Fig. 3). Below 800 degree days, however, the survival rates were more variable, and were low in the most northerly sites monitored 18 and 25–27 years after planting (Hansson and Karlman 1997; Mäkitalo et al. 2010) (Fig. 2).

MSP also reduces weed competition, which influences the availability of water and nutrients, in addition to having effects like reducing shade and mechanical stress, affecting both seedling survival and growth. Munson et al. (1993) concluded that interaction with other vegetation was the most important factor affecting seedling growth, and a number of studies indicate that reducing competition is a major determinant of the success of site preparation (Nilsson et al. 1996; Staples et al. 1999; Nilsson and Örlander 1999b; Nilsson et al. 2010; Parker et al. 2010; Thiffault et al. 2010; Johansson et al. 2013a).

According to Elfving (1992), seedling mortality is greatest during the first five years after planting but may continue up to 15–20 years, based on observations of 1590 regeneration sites stocked mainly with Scots pine in the northern region of Sweden. No such long-term data are available for the southern areas. Even though most of the mortality had probably occurred by the time of data collection in most experiments included in our analyses, some further mortality may have occurred, especially in the youngest Norway spruce and Scots pine studies monitored 3–4 years after planting. However, the suggested mean survival rates for the three species can be considered relevant estimates of probable survival rates in the focal region and give an idea of stem densities in the future forest stands.

The seedlings in the collated studies were protected with an insecticide in most of the experiments with Norway spruce, and in most of the Scots pine experiments in the central and southern parts of both Finland and Sweden (Tables 1 and 2). In many of the southern Swedish experiments, insecticide treatments were repeated in the field once or several times during a period of one to three years after planting. In the more northerly experiments in Finland and Sweden, mainly with Scots and lodgepole pine, the seedlings were probably not protected (Tables 1 and 2). However, in many of the experiments with unprotected seedlings, pine weevil occurrence seemed to be low at the time of planting, and frequencies of both seedling damage and mortality caused by pine weevils are much lower in the northern part of the focal region (Nordlander et al. 2011; Johansson et al. 2015; Nordlander et al. 2017). Thus, the results presented are probably representative of survival rates at sites where pine weevils have moderate influence, and the suggested generalized survival rates and MSP-effects apply to seedlings that are protected against pine weevils or planted at sites with very low (or no) pine weevil populations. If non-protected seedlings are planted, substantially stronger MSP-effects on survival can be expected, but lower survival rates (Fig. 4). This is not surprising as the risk of damage by pine weevil is lower for seedlings surrounded by pure mineral soil than for seedlings surrounded by humus or mixtures of humus and mineral soil (Björklund et al. 2003; Petersson et al. 2005), as shown in many site preparation experiments (Söderström et al. 1978; von Sydow 1997; Örlander and Nilsson 1999; Thorsén et al. 2001). On average, the mortality reported in the collated studies at no MSP sites was 50 p.u. higher for non-protected Norway spruce and Scots pine seedlings than for protected seedlings (Tables 1 and 2). Eventually, planting spots will be colonized by vegetation, and risks of pine weevil damage will then increase (Örlander and Nordlander 2004; Petersson et al. 2005). Hence, the practical advice is to use site preparation methods that create planting spots with predominately mineral soil on the soil surface and plant soon after final cutting, while competing vegetation density is low.

In comparison to results reported herein, more variable effects have been detected in North American studies in terms of survival following MSP, depending on weed competition, thickness of the organic layer, temperature, soil moisture and other environmental factors at the investigated sites. For instance, Bedford and Sutton (2000) reported similar or slightly lower survival rates of lodgepole pine following eight MSP methods compared to those in control plots. This was attributed to small amounts of competing vegetation and some of the MSP methods causing low soil moisture content as the soils had limited water-holding capacity. Moreover, Bedford et al. (2000) found that mounding and ploughing increased survival rates of white spruce (*Picea glauca* (Moench)

Voss), while patch scarification and blading, both of which removed the forest floor, had negative effects on survival (attributed to drowning of seedlings and frost heaving). In contrast, Burgess et al. (1995) found clear positive effects of blade scarification (20%) on survival of white spruce and white pine (*Pinus strobus* L.), due to reduction in vegetation competition. Graham et al. (1989) found lower survival of Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Idaho after planting in mounded soil beds (without herbicide application) than in control plots and after scalping, which removed organic matter and surface soil layers. They also found that mounding increased competition from grasses in the soil beds. These more variable effects on survival rates reported in the North American studies may, at least partly, be due to different and more variable climate and ecological contexts compared with our focal region in Fennoscandia.

5.1.2 Tree height

Based on the experimental data, our study reveals that most of the examined MSP-methods generally increased tree height by 10–25%, relative to No MSP, 10–15 years after planting (Table 3). Ploughing appeared to result in a stronger growth response than the other methods, although this was not statistically significant (few observations), suggesting that caution is required when drawing conclusions about the generality of that trend. In the Finnish survey studies of Norway spruce and Scots pine, mounding mainly resulted in a greater MSP-effect than disc trenching.

In North American studies, MSP in the form of disc trenching, mounding or ploughing is often reported as increasing seedling height growth (Bedford and Sutton 2000; Bedford et al. 2000; Thiffault and Jobidon 2006; Thiffault et al. 2010). This is consistent with our findings. However, treatments that remove the organic layer at planting spots, like blade scarification or scalping, sometimes reportedly resulted in reduced growth (Graham et al. 1989). Bedford et al. (2000) also found that patch scarification reduced growth of white spruce. This was attributed to frost heaving and lack of nutrients available to seedlings planted in the furrows. However, both Simard et al. (2003) and Bedford and Sutton (2000) reported greater height of lodgepole pine after patch scarification.

As for survival (section 5.1.1), reduced weed competition resulting from MSP is beneficial for tree growth. MSP methods that bury the humus layer or mix it with mineral soil stimulate mineralization and hence increase the nutrient availability (McMinn 1985; Nordborg and Nilsson 2003; Nordborg et al. 2003). This could be a reason for the tendency for greater MSP-effects on height development associated with disc trenching, mounding, soil inversion and ploughing in contrast to patch scarification in our study. Patch scarification or scalping, which removes the humus layer, may reduce nutrient availability for seedlings planted in pure mineral soil (Munson et al. 1993; Nohrstedt 2000; Nordborg et al. 2003). This may explain the relatively weak MSP-effect of patch scarification apparent in our study, as well as in Graham et al. (1989) and Bedford et al. (2000).

MSP can also loosen compacted subsoil (Ritari and Lähde 1978; Örlander et al. 1990; Bedford and Sutton 2000) and increase aeration of wet soils (Sutton 1993), thus improving root growth and seedling establishment (Nordborg et al. 2003). However, the results are highly method-dependent and seem to coincide with the trends in MSP-effects on tree height identified in this study: ploughing results in the strongest and deepest loosening, soil inversion, mounding and disc trenching (at least in the berm) cause some loosening, while patch scarification causes very little.

The effects of MSP on soil temperatures mentioned above (section 5.1.1.) may be more beneficial in a harsh climate, as suggested by the trend towards a smaller MSP-effect on tree height with increasing temperature sum at the regeneration sites (Fig. 5). Finally, as shown in earlier studies and these collated data, mortality and damage by pine weevil are reduced by MSP, the latter being clearly beneficial for the growth of planted conifer seedlings.

It should be noted that height growth responses to MSP may be temporary. This is indicated by the curvilinear trends shown in Fig. 5. Repeated measurements in experiments of two of the cited studies, one reported by Johansson et al. (2013a), and the other by Fries (1993) and Hansson and Karlman (1997), support the hypothesis that MSP has temporary effects. In the most long-term Norway spruce study included here, the 20% greater height following mounding or soil inversion compared to No MSP occurred prior to age 14: there were no detectable differences in height growth among the treatments during the 14- to 18-year period after planting (Johansson et al. 2013a). Similarly, MSP-effects of patch scarification and disc trenching after 18 years were very similar, or less than, those recorded after 13 years, and the relative differences decreased (Fries 1993; Hansson and Karlman 1997). Thus, these studies and our collated data indicate that there are temporary growth responses to MSP during the first 10–15 years after planting. After that, the height differences probably persist, but without further increases.

5.2 Disturbed soil surface area and natural regeneration densities

One problem with comparisons of data pertaining to proportions of disturbed soil surface area is that different inventory methodologies were used in the studies. Moreover, the methods were not always fully described, e.g. between-row spacing, further hindering any comparison. For example, substantial variation in the results is due to the exposed area of mineral soil being measured in some cases, while in others the total area affected by the specific MSP-unit used (although the same MSP-method) or the total area disturbed by all the machinery, including wheel tracks etc., was measured. In addition, use of different types of equipment for each of the MSP-methods inevitably affected the results to some extent.

Logically, a patch-based method should disturb a smaller area of the soil surface than a continuous method. Similarly, mounding, because it is a patch-based method, should generally cause less disturbance than disc trenching or ploughing. However, in the reviewed studies there were large variations in proportions of soil surface area reportedly affected by each of the site preparation methods. Furthermore, somewhat unexpectedly, the single studies of patch scarification and soil patch inversion methods indicated that the proportions of the soil surface area they affected were larger than the proportions affected by mounding, being similar to the average proportions affected by disc trenching. Based on the collated data, our study suggests that mounding generally affects about 30–40% of the soil surface area. Patch scarification and soil inversion should affect similar proportions, while proportions affected by disc trenching and ploughing should be higher (45–55% and 55–65%, respectively).

Several studies indicate that site preparation affects densities of naturally regenerated seedlings (Table 5). This is partly because soil disturbance promotes the germination of seeds, and in Fenno-Scandinavian clearcuts broadleaved species (notably birch) are likely competitors. Despite substantial variation in reported results, densities of seedlings tend to be higher after MSP by continuous methods, like disc trenching, than after patch-based methods, such as mounding and inverting. In terms of overall abundance, most seedlings are found in undisturbed areas of stands, but more per unit area are found in scarified areas (Lehtosalo et al. 2010). The number of years after planting also influences densities of naturally regenerated seedlings, among many other inter- and intraspecific factors such as dynamics of competition between seedlings, climatic factors, distance to seed sources and variation in mast years (Holmström et al. 2017). Hence, measuring and drawing conclusions about effects of site preparation on naturally regenerated seedlings is far from straightforward.

5.3 Methodological considerations

In this compilation and analysis of a large dataset, some statistically significant differences between the investigated MSP methods were found with respect to survival rates and growth of subsequently planted seedlings. However, the results of the statistical analyses should be interpreted cautiously due to the limited and unbalanced data, preventing the testing of some interactions that could be of importance, e.g. site × MSP-method and tree species × MSP-method. The dataset included a limited number of studies of some of the MSP methods, e.g. ploughing. Generally, there have been few studies of effects of MSP methods on Scots pine and lodgepole pine. Other limitations are that the MSP methods have not been systematically and consistently tested under diverse site conditions across the region, and the response periods and monitoring times cover different years and thus different weather conditions. Moreover, as discussed above, different methods have different effects on environmental factors. Thus, conscious choices of the method(s) expected to be most appropriate at specific sites may have contributed to small between-method differences in results. Other limitations include a lack of No MSP controls in several studies, and variation in the MSP and planting procedures employed in different studies. In some cases, the MSP has been "simulated" manually in the field, which hinders evaluation of the results in relation to the effects of using machinery in practical operations. Furthermore, as already mentioned, the survival and early development of a seedling depends not only on the chosen MSP method but also on various other factors such as seedling type (including breeding material and provenance), quality and handling, quality of the chosen planting spot, climatic and other physio-chemical factors, and the planting procedure. Nevertheless, the results presented provide general estimates of MSP-effects on survival rate and tree height of the investigated coniferous species.

5.4 Implications of the results

In both Finland and Sweden, cost-efficiency has increased less in recent decades for regeneration measures than for forest harvesting operations (Brunberg 2014; Uotila 2017). Therefore, it is important to find ways to reduce costs, but also maintain or improve regeneration results. In this context, the regeneration chain concept may be helpful for optimizing overall costs of site preparation measures, planting and pre-commercial thinning, thereby maximizing profitability over stand rotations. It is also important for forest owners to be able to choose and apply appropriate forestry measures to obtain results consistent with the goals set for the regeneration efforts.

Uotila et al. (2010) found that both net present value (at 0–5% interest rates) and profitability after first commercial thinning were higher when the more expensive mounding was applied rather than disc trenching with subsequent planting of Norway spruce (in both cases). This was attributed to mounding resulting in higher survival and higher growth rates of Norway spruce seedlings (main tree species) and fewer broadleaves emerging with lower growth rates than after disc trenching. Thus, the study indicated that interactions between site preparation methods and later forest management measures influence the profitability of possible regeneration chains.

Several authors have developed decision support systems for ranking regeneration systems (Ackzell 1993; Hyytiäinen et al. 2006; Nilsson et al. 2006; Miina and Saksa 2006, 2008, 2013), some of which are also intended to help selection of site preparation methods prior to planting (Ahtikoski et al. 2010). Some of these systems take the early development of seedlings into account (Miina and Saksa 2006, 2008, 2013), while others consider the whole regeneration chain (Uotila et al. 2010) or even whole stand rotations (Zhou 1999; Hyytiäinen et al. 2006). Regardless of the extent of these decision support systems, in order to compare regeneration chains with diverse combinations of measures in terms of total costs, results and financial outcome, it is

necessary to quantify effects of individual measures. The information compiled in this study may assist the prediction of future needs and costs for pre-commercial thinning as well as development of the main tree crop. Thus, this work may facilitate the design and analysis of appropriate regeneration chains.

6 Conclusions and future research

MSP can increase survival rates of planted conifer seedlings by 15–20 p.u. in general, resulting in 80–90% survival ca. 10 years after planting Norway spruce, Scots pine or lodgepole pine in Fennoscandian mineral soil sites. Low or absent pine weevil populations or efficient protection of planted seedlings are prerequisites for that survival rate. All the considered MSP methods also generally resulted in 10–25% greater tree height 10–15 years after planting. The increase in growth rate associated with MSP may be temporary, but the height enhancement probably persists. In addition, the MSP effects on tree height seemed to be weaker when temperature sums are large. The investigated MSP methods commonly result in quite high proportions of disturbed soil surface area, which may be a drawback aesthetically, and cause high densities of unwanted natural regeneration that will have to be cleared at high cost.

Information on survival, growth and yield from field trials is necessary to be able to make decisions concerning different regeneration choices. In that context, there is still a need for more information and comparative studies examining the effects of different site preparation methods at different sites on the survival and growth of seedlings (especially Scots pine), as well as on the establishment and growth of unwanted natural regeneration and requirements for curbing it when different MSP methods are employed at different sites. Existing field trials must be monitored regularly, over a sufficiently long period to assess the future production stock and thus robustly evaluate effects of the measures undertaken. New field trials must be established systematically and in a standardized manner to cover different soil types and climate conditions. There is also a need to develop predictive models for the biological and financial success of different regeneration chains, which should be easy to follow up and evaluate. Moreover, development of site preparation methods that reduce proportions of affected land area without compromising the creation of adequate numbers of high-quality planting spots will be challenging, but important for environmental, financial and aesthetic reasons, and thus for the acceptance of MSP by the general public.

Acknowledgements

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