

Pinus contorta Growth in Boreal Sweden as Affected by Combined Lupin Treatment and Soil Scarification

Stefan Mattson, Urban Bergsten and Tommy Mörling

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Effects of combining lupin (*Lupinus nootkatensis* L.) establishment and soil scarification on stem volume and stem biomass yield of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) were studied on a poor boreal site in Sweden 18 years after plantation. A field randomized block experiment was established with three different scarification techniques (disc trenching, moulding and ploughing) followed by establishment of lupins by either seeds or roots. There were three blocks without and two blocks with lupins. Overall, on average for the three soil scarification techniques, the lupin treatment significantly increased the volume per hectare by 102%. The lupin treatment significantly increased the stem volume per hectare by 236% for mounding and 139% for disc trenching, whereas the 55% increase for ploughing was not significant. The increase in the total stem biomass yield per tree was more pronounced for larger trees; 46% for average trees and 106% for dominant trees. However, there were no significant differences between scarification techniques for the lupin treatment in total stem biomass yield. Over the 18-year period, the increased growth rate following the lupin treatment resulted in a significantly decreased average stem basic wood density (on average 6%) for the sample trees. Because lupin is a nitrogen-fixing plant species, the large increase in tree growth following the lupin treatment was probably an effect of increased amount of nitrogen in the soil. The results indicate that use of lupin is a possible alternative to increase site productivity of lodgepole pine on poor boreal sites.

Keywords biomass, cultivation, lodgepole pine, *lupinus*, nitrogen inputs, wood density

Addresses Swedish University of Agricultural Sciences, Dept of Forest Ecology and Management, SE-901 83 Umeå, Sweden

E-mail tommy.morling@ssko.slu.se

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1 Introduction

Site preparation techniques such as prescribed burning and soil scarification commonly are used to improve establishment and growth of forest plantations (Sutton 1993, Savill et al. 1997). In Swedish forestry, techniques such as disc trenching and mounding are normally used. Positive effects on survival and short-term growth have been reported (Barring 1965) and can be explained by the positive effects of soil scarification on external growth factors: increased soil temperature (Kubin and Kemppainen 1994), better light availability, lower soil bulk density (Lähde 1978), better water and oxygen conditions (Thompson 1984), increased nutrient mineralisation (Rosén and Lundmark-Thelin 1986), decreased competition from vegetation and decreased damage caused by *Hylobius abietis* L. (Söderström et al. 1978, Örlander and Nilsson 1999).

Nitrogen is the limiting plant nutrient in most forest ecosystems in Sweden (Tamm 1991). Nitrogen-fixing plant species can reduce atmospheric nitrogen by symbiosis with nitrogen fixing bacteria (Sprent and Sprent 1990). In legumes, such as lupins, the nitrogen fixation is performed by single-cell eubacteria, rhizobia, in root nodules. Hence, these plants can use atmospheric N₂ as a nitrogen source. Lupins are therefore a nitrogen-fixing plant genera, which might increase the soil nitrogen levels and could therefore be beneficial for tree growth, especially on nitrogen-poor sites. Lupins have also been reported to increase nitrogen availability and site productivity in e.g. Australia (Smethurst et al. 1986, Nambiar and Nethercott 1987), New Zealand (Dawson 1983, Gadgil 1983, Gadgil and Ede 1998) and Iceland (Riege 2004). However, there are few studies that examine the effects of lupin in boreal forests (Tamm 1947). Hesselman (1917) mentions the positive effect of lupin on height growth of young Scots pine on a pine heath in south-western Sweden. Alaska lupin (*Lupin nootkatensis* L.) has also been shown to perform well and to increase soil nitrogen availability on nitrogen poor sites in northern Sweden (Huss-Danell and Lundmark 1988, Myrold and Huss-Danell 2003). However, the effect on tree growth remains to be evaluated.

When comparing silvicultural treatments, biomass production is often a more relevant characteristic than volume growth, because it takes into account both volume and density of wood. Wood density is also an important characteristic to analyse because of its influences on the quality of many end products, such as pulp and paper yield (Zobel and van Buijtenen 1989). It has also been shown that silviculture treatments that affect growth rate also affect wood density. For instance, a negative relationship between ring density and ring width has been found for *Pinus contorta* (Middleton et al. 1995) and *Pinus sylvestris* L. (Dorn 1969, Mörling 2002).

Pinus contorta (Dougl. var. *latifolia* Engelm.) was introduced to Sweden as a mean to increase wood production on primarily intermediate and poor sites compared to native *Pinus sylvestris* (Elfving et al 2001). It has also been found to establish and grow well on these sites whereas fertile and moist sites are avoided due to problems with stability and pathogens.

Previously reported studies on effects of soil scarification without lupin treatment on survival and growth from the same experiment as examined in the present study, have shown that growth had increased with increased proportion disturbed soil area and that growth differences between treatments have increased over time (Hunt 1987, Jansson and Näslund 1993, Mattsson and Bergsten 2003). A possible explanation for these growth differences could be that nitrogen availability in the soil increases with increasing proportion of disturbed soil area (Johansson 1991). For the present study we therefore hypothesised that lupin establishment would increase stem volume and biomass growth, but that the relative increase would be negatively related to the amount of disturbed soil area. Our objective was to quantify the effects of lupin on tree growth for mounding, disc trenching, and ploughing, i.e. methods with different intensity of soil disturbance. The growth evaluations were made on an 18-year-old lodgepole pine stand (*Pinus contorta* Dougl. var. *latifolia* Engelm.) field experiment on a poor boreal site, and growth was evaluated by analysing stem volume, wood density and stem biomass.

2 Materials and Methods

2.1 Site and Trial Description

The trial used in this study is situated at Böle, ca 100 km south of Östersund, in Central Sweden. According to the Köppen climate classification system (Köppen 1923), the area is located in a cold temperate humid climate type. The site climate (average 1961–1990) is characterised by an average temperature of +3.4°C with annual precipitation close to 600 mm. The basic geology of the area is Rätan granite, which has a medium weathering capacity (Troedsson and Nyqvist 1973). The site is poor in terms of site productivity and dry due to very coarse soil texture (Hunt 1987). The site is a degenerated heath that was burnt at the beginning of the 20th century (Table 1).

The experiment used in this study had a randomised plot design and consisted of two parts. Part one consisted of 16 plots with four replications of four treatments (three cultivation methods plus control). For this study nine of these 16 plots were used for analysis, since all uncultivated control plots were excluded and one complete subset of cultivated plots (i.e., one replication of each cultivation treatment) was not used because it was established in a frost prone area to study effects of cultivation method on seedling frost damage. Part two consisted of six plots treated with lupin (two plots of each soil cultivation method, no untreated control). Therefore, there were three replicates of each soil cultivation treatment without lupin and two replicates of the soil cultivation treatments with lupin. The six plots with lupin treatment were located adjacent to the other plots. The size of each gross plot was 50×50 m, with a 30×30 m net plot. A 10 m wide treated buffer zone thus surrounded each net plot. For a map of the experimental area, see Hunt (1987). The experiment is part of a larger experimental series to evaluate soil scarification effects on tree growth on four different site types (see Hunt 1987, Mattsson and Bergsten 2003)

Cultivation was carried out in August 1981 using the following techniques: ploughing (Lönntek plow, Olofsfors Bruk AB, Sweden, approx. 0.5 m between undisturbed soil and bottom

Table 1. Site characteristics at the time of experiment establishment 1981.

Features	
Geographic location	62°27'N, 14°20'E
Site features	flat, dry, > 2 m to groundwater
Soil texture	sediment, stoney washed gravel
Soil type	lichen podsol – ordinary iron podsol
Temperature sum ($\geq +5^\circ\text{C}$)	865
Vegetation period (days)	151
Elevation (m)	410
Vegetation type ^a	Lichen
Total amount of Nitrogen in humus layer (kg/ha)	210
Site Index ^b	T14

^a Estimated by Hunt (1987) according to Hägglund and Lundmark (1977).

^b Dominant height (m) in even-aged stands at 100 years of total age (T = Scots pine). Estimated by Hunt (1987) according to Hägglund and Lundmark (1977).

furrow), disc trenching (Murveln disc trencher, AB Järvsö Skogsmekan, Sweden, powered disk rotation with down pressure), and mounding (Bräcke Mounder, Robur Maskin AB, Sweden, mound volume was at least 10 litres), see Wickström (1981) for a description of the scarifiers and Hunt (1987) for description of soil profiles of the different techniques. The approximate percentage of disturbed soil area according to Lundmark (1986) was 69% for ploughing, 54% for disc trenching, and 35% for mounding. In autumn 1981, lupin treatments were installed: three plots with lupin roots and three where established with lupin seeds. The lupins were planted or sowed in the exposed mineral soil in every second furrow or mound i.e. 4 m×4 m spacing (625 per ha). The planted lupin roots were about 10 cm in length, and 4–5 seeds were sowed in each spot. At the time of the present study in 1998/1999, the lupin covered the mineral soil exposed during cultivation. Unfortunately, there was no detailed information available on lupin cover for the individual plots or treatments.

One-year-old lodgepole pine (*Pinus contorta* Dougl. var *latifolia* Engelm) container seedlings (Kopparfors 1/0) were planted in June 1982 at 2000 seedlings per hectare. The seedlings were planted in a raised position in the middle of the

cultivation area (at the highest position in the mineral soil in the disc trenching track, in the mound and on the ploughed tilt), with the plug surface 2 cm below the soil surface. Supplementary planting to replace dead seedlings was made in August 1983 and in June 1984. At the time of the 1998/1999 assessment, the average number of trees in the plots was about 91% of the number of planted seedlings at the establishment of the experiment (Table 3).

2.2 Field Measurements and Collection of Wood Samples from Sample Trees

Height and diameter at breast height (DBH, 1.3 m) were measured in autumn of 1998 and in spring of 1999 before the growing period started. All trees above 1.3 m were measured for diameter using a cross-calliper. Height was measured using an electronic hypsometer (Vertex) on about 20 sample trees per plot, the five largest diameter trees, plus fifteen randomly sampled trees. This method of sampling, i.e. over representation of large diameter sample trees, has been proven to give efficient and unbiased estimates (Karlsson 1999). This is due to the large influence large trees has on total standing volume. In total, 2066 trees were measured for diameter and 295 trees were measured for height on fifteen sample plots.

In autumn 1998 and spring 1999, the sampling for the biomass analysis was carried out on the six lupin plots and on six plots of the nine plots without lupin, two of each cultivation treatment. The plot mean stem diameters were calculated along with the average stem diameter for the nine largest DBH trees in each plot (100 largest trees ha⁻¹). Four sample trees were chosen from each plot, within 10% of these calculated plot mean stem diameters, two representing the average and two representing the dominant trees. The reason for sampling average and largest trees was that these trees represent those that probably will constitute the mature stand and it also makes it possible to analyse the treatment differences between tree sizes. In total, 48 sample trees, straight and without stem defects, were collected from the gross plot, outside the net plots. The sample trees were not taken from the net plots because the latter were being kept intact for future measurements.

However, the wood density properties of the sampled trees should not differ from the properties of the trees inside the net plot since they were of the same age and from the same diameter range.

The sample trees were felled at 0.15 m above ground level (stump height), and 50 mm thick stem discs were collected between every third whorl. Depending on the age at stump height, five or six stem discs were collected from each tree. For example, 16-year-old trees had six collected discs with the cambial age of 16, 14, 11, 8, 5, and 2 years while 13-year-old trees had five collected discs with the cambial age of 13, 11, 8, 5, and 2 years. In total, 286 discs were collected from 24 average and 24 dominant sample trees. Prior to freezer storage, each of the discs was marked, given an ID-number, and the distance between each whorl was recorded to the nearest mm.

2.3 Calculation of 18-year Stem Volume Yield

Stem volume functions were used for two tree size classes: 1) larger trees, dbh ≥ 50 mm, and 2) small trees, dbh < 50 mm. By using the diameter and height values for the trees on the plots (about 20 trees per plot), secondary volume functions were developed. The stem volume for the other trees on the plots was calculated using these secondary volume functions.

The stem volume of the larger trees was calculated using volume functions developed by Eriksson (1973) for lodgepole pine in Sweden. The stem volume of the small trees was calculated using volume functions for small Scots pine trees in northern Sweden (Andersson 1954). Secondary volume functions were developed using regression analysis for height and diameter (Jonsson 1978, Krumland and Wensel 1978). One secondary volume function was made for all soil cultivated plots without lupin treatment, and another function was made for the plots with the lupin treatment. The volume of all trees within the plots was then calculated using these functions, with a logarithm for the volume and a correction for logarithmic bias:

$$\ln(V) = b_0 + \frac{1}{2}s^2 + b_1 \ln(d) + b_2 (\ln(d))^2 \quad (1)$$

Where V is the stem volume, s is standard deviation, d is tree diameter at breast height, and b_0 , b_1 , and b_2 are coefficients estimated from the sample tree data.

2.4 Calculation of Stem Volume, Wood Density and Stem Biomass for Sample Trees

All discs except those with the cambial age of two years were analysed for annual ring development and annual wood density. The discs were immersed in water for 24 hours and then the surface was planed perpendicular to the stem. Each disc was scanned and growth rings were measured on two opposing radii (north and south) using the WinDendro software (Guay et al. 1992). The stem volume production for each year was calculated within each tree section (cf. Loetsch et al. 1973), based on truncated cones (V_t). In the section containing the top of the tree, calculations were made only on the volume of cones (V_c) using the following formula:

$$V_c = \frac{1}{3} g l \quad (2)$$

Where g is basal area at bottom of cone, and l is the length of cone. The volume of truncated cones (V_t) was calculated using the following formula:

$$V_t = \frac{1}{3} \pi L (R^2 + R r + r^2) \quad (3)$$

Where L is the length of section, R is the radius at bottom of the section, and r is the radius at top of the section. The radius was calculated by averaging radii in the north and south directions. The volume produced in a specific year (V_Y) was calculated using the following formula:

$$V_Y = \sum_{i=1}^n V_{Y_i} - V_{(Y-1)_i} \quad (4)$$

Where V_{Y_i} is volume produced until year Y in section i , $V_{(Y-1)_i}$ is volume produced until year $Y-1$ in section i . For each of the sample discs, one cardinal point (south, north, west, or east) was randomly selected. When compression wood was present, which was based on the visual determination that >30% of a year ring consisted of dark coloured wood, the cardinal point with the

least amount of compression wood was selected. Wood sample specimens (approx 9 mm × 9 mm) were taken from each of the sample discs in the randomly selected direction using a band-saw. The sample specimens were soaked in acetone for 72 hours (nine parts of acetone and one part of water), and then air-dried at 20°C for 48 hours. The wood sample specimens were reduced to approximately 2 mm × 5 mm in longitudinal and tangential direction using a twin-blade circular saw (cf. Larsson et al. 1994). The density profile in the longitudinal direction for the 227 wood sample specimens was measured batch-wise using Woodtrax X-ray micro densitometry (Bergsten et al. 2001). The tangential and radial measurement resolution was 25 × 25 μm, corresponding to 40 measurements every mm. The micro densitometry data obtained was processed using the software Density (Cox 1999) to determine the annual ring density and average wood density for each wood specimen. The density values from the X-ray measurements were calibrated by gravimetric measurements. The average density was measured gravimetrically for each of the air-dried specimens. In addition, 44 specimens were kiln-dried for 8 h at 103°C (Megraw 1985) until no further loss in weight was observed. A linear regression model (kiln-dry density = 9.36 + 0.908 air-dry density, $R^2 = 98.8$) was developed using the air-dry and kiln-dry densities (kg m⁻³) for the wood specimens. Kiln-dry densities were then calculated for the other specimens using the regression model. For each section and year ring, the volume was multiplied by the kiln-dry density to obtain the annual biomass production. To calculate the basic density, the biomass was divided by the green volume.

2.5 Statistical Analysis

The statistical calculations were accomplished by using Minitab 13.2 (Minitab Inc). The secondary volume functions were made using the linear regression procedure. To meet the prerequisites for analysis of variance (ANOVA), the volume and biomass values were log-transformed. The plot means were used as observations and assumed to be normally distributed. ANOVA was performed using the general linear model (GLM) procedure.

Treatment was considered as a fixed factor. It was not possible to test interaction effects because of the low number of observations. When significant treatment effects were found, Tukey’s test (e.g. Zar 1999) was used to test significant differences ($p \leq 0.05$) between treatments.

3 Results

The effects of soil scarification and lupin treatment on 18-year stem volume production were statistically significant (Table 2). Overall, lupin treatment increased volume increment by 3.2 m³ sub ha⁻¹ (sub =solid under bark) with very small differences between the soil scarification treatments (Table 3). The lupin treatment significantly increased the relative 18-year stem volume per hectare by 143% on average, The relative increase for lupin treatment was for mounding + 236% and for disc trenching +139%, whereas, the relative increase for ploughing (+55%) was non-significant. The lupin treatment originating from lupin

roots produced about 75% more stem volume compared with lupin originating from seeds, but the difference was not significant due to limited replications (data not shown). Ploughing significantly increased the 18-year stem volume compared to disc trenching and mounding. However, there were no significant differences between disc trenching and mounding, again due to the limited number of replicates.

Table 2. Effects of soil cultivation treatment and lupin treatment on 18-year stem volume yield (m³sub^a ha⁻¹) according to the ANOVA with sums of squares (SS) expressed as percent of total SS

Source of variation	Df	Volume yield		P
		SS%	F	
Lupin treatment	1	35.2	19.57	0.001
Soil cultivation treatment	2	45.0	12.49	0.001
Error	11	19.8		
Total	14			

^a Solid under bark

Table 3. Effects of lupin treatment and soil cultivation treatment on 18-year survival and growth. Values with different letters are significantly different according to Tukey ($p \leq 0.05$). Small letters compare the soil cultivation treatments and capital letters the effect of lupin for each soil cultivation treatment.

	No lupin	Lupin
Number ¹ of living saplings		
Disc trenching	1933	1683
Mounding	1866	1805
Ploughing	1961	1916
Height ² (m)		
Disc trenching	2.6	3.3
Mounding	2.3	3.0
Ploughing	3.2	3.6
Diameter ³ (cm)		
Disc trenching	2.4	3.9
Mounding	2.3	3.5
Ploughing	3.6	4.4
Volume yield ⁴ (m ³ sub ha ⁻¹)		
Disc trenching	2.3 <i>aA</i>	5.5 <i>bB</i>
Mounding	1.4 <i>aA</i>	4.7 <i>bB</i>
Ploughing	5.6 <i>aA</i>	8.7 <i>aA</i>

Note: ¹ Number per ha. ² Average height of sample trees (about 20 trees per plot). ³ Average DBH (1.3 m) of all trees on the plots. ⁴ Stem volume of all trees on the plots, sub = solid under bark

Table 4. Annual stem biomass production (g) of average sample trees, and mean annual biomass production above stump height (MAI) (g) of average and dominant sample trees for the 18-year period. A denotes average trees, D denotes dominant trees. Each value represents the arithmetic mean of two plots with two sampled trees per plot. Min and max values for plot MAI are given in parentheses.

	No lupin treatment			Lupin treatment		
	Di	Mo	Pl	Di	Mo	Pl
Average trees	58	58	117	147	88	135
(min–max)	(57–58)	(51–66)	(79–155)	(140–154)	(70–106)	(106–164)
Dominant trees	112	105	190	289	226	282
(min–max)	(101–123)	(83–127)	(170–210)	(237–341)	(209–244)	(198–367)

Note: Di=disc trenching, Mo=mounding, Pl=ploughing

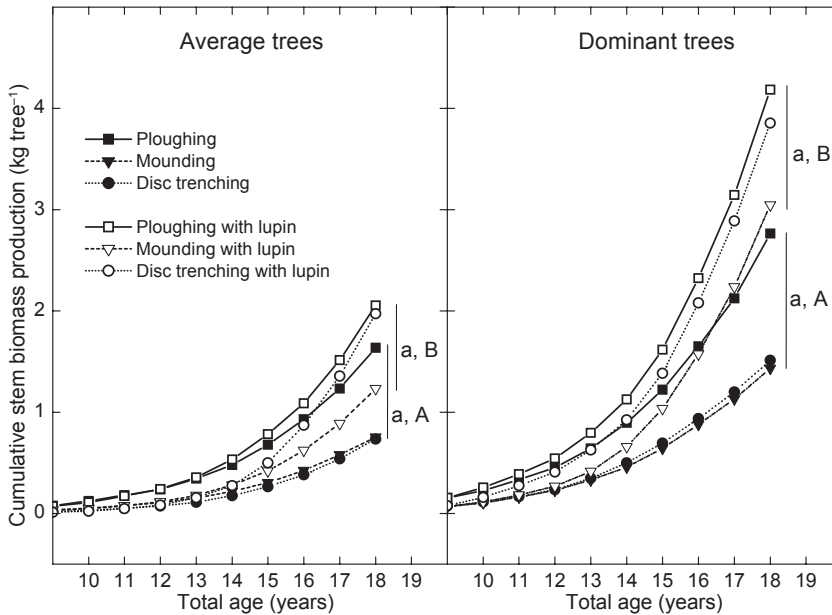


Fig. 1. Cumulative stem biomass production above stump height for sample trees. Each point represents an average of four trees. For year 18, values with different letters are significantly different according to Tukey ($p \leq 0.05$). Small letters compare the soil cultivation treatments and capital letters the effect of lupin.

The lupin treatment significantly increased the 18-year stem biomass production for the sample trees compared to no lupin treatment. On average, the biomass production per tree was respectively 68% and 94% higher (0.7 kg and 1.8 kg) following the lupin treatment, for the average and dominant sample trees, respectively (Table 4). For the plots without lupin treatment, ploughing significantly increased the 18-year stem biomass production for the average (120%) and dominant (88%) sample trees compared to disc trenching and mounding. However, for the plots treated with lupin the stem biomass production was similar for ploughing and disc trenching, i.e. higher than mounding.

The mean annual increment (MAI) of biomass for the sample trees was higher for the lupin treatment compared to no lupin treatment, but there were no significant differences between the cultivation treatments. On average, the MAI for the average and dominant sample trees was 59% and 96% higher for the lupin treatment compared to no lupin treatment (Table 4).

The average stem basic density for the sample trees decreased with increased tree age. Over the

18-year period, the increased growth rate following the lupin treatment resulted in a statistically significantly lower average stem basic density of 5% (21 kg m^{-3}) and 7% (28 kg m^{-3}), for the average and dominant sample trees, respectively (Fig. 2).

4 Discussion

In general the results supported the hypotheses that lupin treatment would increase growth and that the relative increase would be negatively related to proportion of disturbed soil area. The added growth in the lupin treated plots was constant over the site preparation methods which indicate that also the increase in available soil nitrogen was constant. Hence, the relative effect of lupins was more pronounced for the soil preparation methods showing the lowest production. Since there were no data available on lupin establishment and abundance over time, soil moisture, and soil nitrogen for the different site preparation

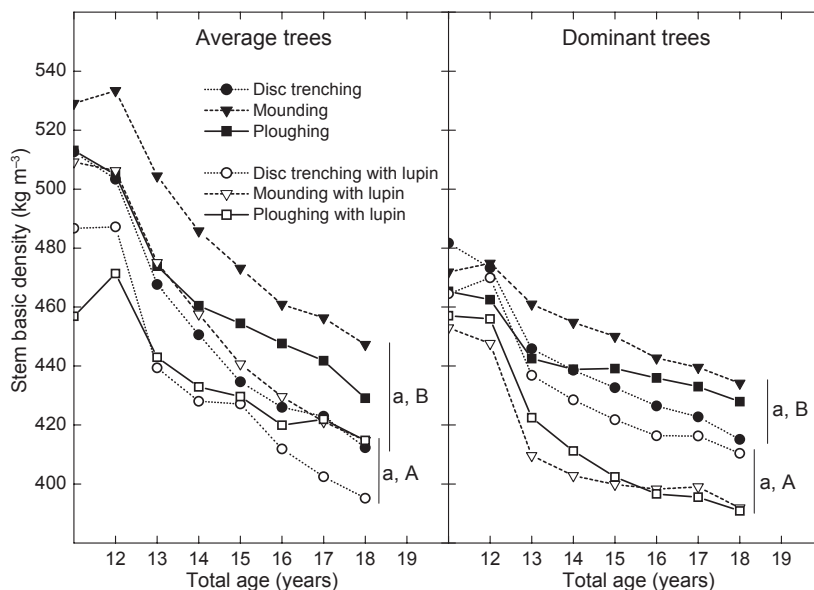


Fig. 2. Development of stem basic density for sample trees. Each line represents an average of four trees. For year 18, values with different letters are significantly different according to Tukey ($p \leq 0.05$). Small letters compare the soil cultivation treatments and capital letters the effect of lupin.

methods and the number of replicates was low, the results should be considered as indicative.

The main objective of the experiment was to analyse the long-term effects of different soil cultivation treatments on tree growth (cf. Mattsson and Bergsten 2003). This explains the low number of replications of the lupin treatments in the experiment. A consequence is the lack of significant differences despite relatively large growth differences between lupin treated and non lupin treated plots (cf. ploughing). Another weakness of the experimental design is that effects of lupin source (roots or seeds) for each soil cultivation method could not be analysed.

However, the experiment still gives information on the possibilities of using lupin to improve growth conditions for lodgepole pine on nitrogen poor sites. Projecting the growth curves for the sample trees (Fig. 1), the growth rate difference between the lupin treatment and the plots without lupin look set to continue into the future. For each cultivation treatment, the growth curves for the sample trees without lupin not only show a delay in time in comparison to the lupin treatment, but also the growth curves show a flatter slope indicat-

ing that the lupin treatment has induced a higher long-term productivity. These results support the increased plant available nitrogen still 20 years following lupin establishment on a poor degenerated site in northern Sweden reported by Myrold and Huss-Danell (2003). Similarly, when comparing the cultivation treatments for the plots without lupin the growth rate difference between ploughing and the other two treatments also look set to continue, see also Mattsson and Bergsten (2003). However, although some studies indicate that soil cultivation results in sustainable increased growth (Pohtila and Valkonen 1985, Mälkönen 1987, Örländer et al. 1990, Örländer et al. 1996), there are indications that nutrient loss from enhanced soil processes could result in reduced long-term site productivity, especially on poor sites and with soils that have a high percentage of disturbed soil (Lundmark 1977, Johansson 1991, Johansson 1994). Therefore, using lupin in combination with gentle soil cultivation on poor sites might decrease the risk of reduced long-term site productivity (cf. Myrold and Huss-Danell 2003).

In a previous evaluation of the part of this trial without the lupin treatment, the influence

of soil cultivation on the turn-over rate of slash and on the dynamics of its nitrogen pool were studied (Johansson 1991). The rates of needle decomposition were affected to about the same extent by ploughing, disc trenching, and mounding. However, the decrease in the nitrogen pool was proportional to the area affected by each cultivation method. The largest pool decrease was obtained at ploughed plots (61%) followed by disc trenched plots (42%) and mounded plots (30%). The beneficial effect of lupin on tree growth was greatest on mounded plots and least on ploughed plots; i.e., the effect of lupin seems to be related to the area/volume of disturbed soil. The reason for this is not clear, but one explanation could be that the large disturbed soil volume caused by ploughing has, due to mineralisation of a large part of the organic material in the field and humus layer, increased the amount of available nitrogen in the soil compared to mounding. Thus, the increased availability of nitrogen in the soil following the lupin treatment might be more important for trees growing on mounded plots with less disturbed soil volume and, hence, less available nitrogen.

When introducing lupin to a site it is important that there is the proper type of *Rhizobium* in the soil (Sprent and Sprent 1990). If the organism is not natural in the soil it has to be introduced. Inoculation of lupin is easily done by mixing the seeds with *R. Lupini*-culture, with soil, or with crushed root nodules from a site with nodulated lupins (Huss-Danell and Lundmark 1988). In this study, the plots with lupin originating from roots produced about 75% more tree volume compared to plots with lupin originating from seeds, although this difference was not statistically significant. Difference might be due to variation in inoculation of *Rhizobium*, or because it takes longer time for lupin seeds to establish sufficient leaf biomass and cover of the exposed mineral soil compared to lupin roots.

Among conifers, an increased growth rate is generally associated with a decrease in basic density (Zobel and van Buijtenen 1989) and this is supported by the results of this study. However, the increase in volume production with lupin treatment is more than compensated for by the decrease in wood density, hence, the lupin treatment also increased the biomass production.

In conclusion, with lodgepole pine on a poor boreal site, initial lupin treatment was shown to increase stem volume and biomass production after 18 years. The relative increase was most pronounced for mounding and disc trenching. The results also indicate that this effect will continue and long-term yield from the site will be improved as an effect of the establishment of lupins which is in accordance with earlier findings that lupin establishment on poor boreal sites can be used to improve long term soil fertility.

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References

- Andersson, S.-O. 1954. Funktionen und Tabellen zur Kubierung kleiner Bäume. Mitteilungen der Forstlichen Forschungsanstalt Schwedens 44(12). 29 p. (In Swedish with German summary).
- Bärring, U. 1965. On the importance of scalping and some other problems connected with planting of *Pinus silvestris* L. and *Picea abies* Karst. *Studia Forestalia Suecica* 24. 80 p. ISSN 0039-3150. (In Swedish with English summary).
- Bergsten, U., Lindeberg, J., Rindby, A. & Evans, R. 2001. Batch measurements of wood density on intact or prepared drill cores using x-ray microdensitometry. *Wood Science and Technology* 35: 435–452.
- Cox. 1999. Manual för programvaran till ITRAX. Cox Analytical Systems AB.
- Dawson, J.O. 1983. Dinitrogen fixation in forest ecosystems. *Canadian Journal of Microbiology* 29: 979–992.
- Dorn, D. 1969. Relationship of specific gravity and tracheid length to growth rate and provenance in

- Scotch pine. In: Schreiner, E.J. (ed.). Proceedings of the 16th Northeastern For Tree Improv Conf, Macdonald College, Quebec, Canada, August 8–10, 1968.
- Elfving, B., Ericsson, T. & Rosvall, O. 2001. The introduction of lodgepole pine for wood production in Sweden – a review. *Forest Ecology and Management* 141: 15–29.
- Eriksson, H. 1973. Tree volume functions for ash, aspen, alder and lodgepole pine in Sweden. Royal College of Forestry, Dept. of Forest yield research. Research Notes 26. 26 p. (In Swedish with English summary).
- Gadgil, R.L. 1983. Biological nitrogen fixation in forestry – research and practice in Australia and New Zealand. In: Gordon, J.C. & Wheeler, C.T. (eds.). *Biological nitrogen fixation in forest ecosystems: foundations and applications*. Martinus Nijhoff/Dr W. Junk, The Hague. p. 317–332.
- & Ede, F.J. 1998. Application of scientific principles to sand dune stabilization in New Zealand: past progress and future needs. *Land Degradation and Development* 9: 131–142.
- Guay, R., Gagnon, R. & Morin, H. 1992. A new automatic and interactive tree-ring measurement system based on a line scan camera. *Forestry Chronicle* 68(1): 138–141.
- Hägglund, B. & Lundmark, J.-E. 1977. Site index estimation by means of site properties. Scots pine and Norway spruce in Sweden. *Studia Forestalia Suecica* 138. 33 p.
- Hesselman, H. 1917. Studier över de norrländska tallhedarnas förnygringsvillkor. Meddelanden från Statens Skogsforskningsanstalt 13/14: 1262–1265.
- Hunt, J. 1987. Mechanical site preparation. Part 1 – Establishment of *Pinus contorta* with different site preparation treatments and site types in Northern Sweden. SLU, Dept. of Silviculture. Report 21. 60 p. ISSN 0281-7292.
- Huss-Danell, K. & Lundmark, J.-E. 1988. Growth of nitrogen-fixing *Alnus incana* and *Lupinus* spp. for restoration of degenerated forest soil in northern Sweden. *Studia Forestalia Suecica* 181. 20 p. ISSN 0039-3150, ISBN 91-576-3516-1.
- Jansson, E. & Näslund, B.-Å. 1993. Markberedningens inverkan på produktionen – data från 10-årsrevision av Rätanförsöket. Institutionen för skogsskötsel, SLU. Arbetsrapporter 72.
- Johansson, M.-B. 1991. The influence of soil scarification on the turn-over rate of organic matter and nitrogen release at clear-cut areas in central Sweden. In: Pihlaja, K. (ed.). Proceedings of the third international nordic symposium on humus substances, Aug. 21–23, 1991, Turku, Finland. *Finnish Humus News* 3(3). p. 35–40. ISSN 0786-7050.
- 1994. The influence of soil scarification on the turn-over rate of slash needles and nutrient release. *Scandinavian Journal of Forest Research* 9(2): 170–179.
- Jonsson, B. 1978. Forest management methods under development at the college of forestry in Sweden. *Sveriges Skogsvårdsförbundets Tidskrift* 76(6): 479–492. (In Swedish with English summary).
- Karlsson, K. 1999. Stem volume estimation and stem shape changes in differently treated Norway spruce and Scots pine stands. SLU, Dept. of Forest Management and Products, Uppsala, Sweden, Licentiate thesis. Report 6. ISSN 1403-9508.
- Köppen, V. 1923. *Die Klimat der Erde: Grundriss der Klimatkunde*. Walter de Gruyter, Berlin.
- Krumland, B. & Wensel, L. 1978. Generalized height diameter equations for coastal conifers. University of California, Berkeley, Dept. of Forestry and Conservation, co-op redwood yield research project. Research Note 8. 10 p.
- Kubin, E. & Kempainen, L. 1994. Effect of soil preparation of boreal spruce forest on air and soil temperature conditions in forest regeneration areas. *Acta Forestalia Fennica* 244. 56 p.
- Lähde, E. 1978. Effect of soil treatment on physical properties of the soil and on development of Scots pine and Norway spruce seedlings. *Communicationes Instituti Forestalis Fenniae* 94(5). 59 p. (In Finnish with English summary).
- Larsson, B., Pernstål, K. & Jonsson, B. 1994. A wood sample preparation method for direct scanning X-ray microdensitometry. SLU, Dept. of Biometry and Forest Management, Umeå. Report 29. ISSN 0349-2133.
- Loetsch, F., Zöhrer, F. & Haller, K. 1973. *Forest inventory. Volume 2*. BLV. Verlagsgesellschaft mbH, München. 469 p. ISBN 3-405-10812-8.
- Lundmark, J.-E. 1977. Marken som en del i det skogliga ekosystemet. *Sveriges Skogsvårdsförbundets Tidskrift* 2: 109–122. (In Swedish).
- 1986. Influence of soil conditions on long-term productive capacity of the sites. In: Bäcké, J., Larsson, M., Lundmark, J.-E. & Örlander, G. (eds.). *Site-adapted scarification – A theoretical analysis*

- of some scarification principles. The Forest Operations Institute of Sweden. Report 3. 48 p. (In Swedish with English Summary).
- Mälkönen, E. 1987. A review of soil preparation in Finland. IUFRO Working Party S1.05-12, Grand Prairie and Dawson Creek, Canada.
- Mattsson, S. & Bergsten, U. 2003. *Pinus contorta* growth in northern Sweden as affected by site type and soil scarification. *New Forests* 26: 217–231.
- Megraw, R.A. 1985. Wood quality factors in loblolly pine. TAPPI Press. Atlanta, Georgia, USA. 89 p. ISBN 0-89852-048-7.
- Middleton, G.R., Jozsa, L.A., Palka, L.C, Munro, B.D. & Sen, P. 1995. Lodgepole pine product yields related to differences in stand density. Forintek Special Publication SP-35. 65 p.
- Mörling, T. 2002. Evaluation of annual ring width and ring density development after fertilisation and thinning in Scots pine. *Annals of Forest Science* 59: 29–40.
- Myrold, D.D. & Huss-Danell, K. 2003. Alder and lupin enhance nitrogen cycling in a degraded forest soil in Northern Sweden. *Plant and Soil* 254: 47–56.
- Nambiar, E.K.S. & Nethercott, K.H. 1987. Nutrient and water availability to growth of young radiata pine plantations intercropped with lupins. *New Forest* 1: 117–134.
- Örlander, G. & Nilsson, U. 1999. Effect of reforestation methods on Pine weevil (*Hyllobius abietis*) damage and seedling survival. *Scandinavian Journal of Forest Research* 14: 341–354.
- , Hallsby, G. & Sundqvist, H. 1990. Survival, growth and nutrient status of a 23 year old Scots pine (*Pinus sylvestris* (L.)) and Norway spruce (*Picea abies* (L.) Karst.) plantation on a ploughed versus burnt lichen site. SLU, Dept. of Silviculture. Reports 26. 48 p. ISBN 91-576-3832-2. (In Swedish with English summary).
- , Egnell, G. & Albrektson, A. 1996. Long-term effects of site preparation on growth in Scots pine. *Forest Ecology and Management* 86: 27–37.
- Pohtila, E. & Valkonen, S. 1985. Development and condition of artificially regenerated pine and spruce sapling stands in the privately owned forests of Finnish Lapland. *Folia Forestalia* 631. 19 p. (In Finnish with English summary).
- Riege, D.A. 2004. The use of *Lupinus nootkatensis* in a revegetation and afforestation program in South-west Iceland. In: Santen, E. van, Hill, G.D. (eds.). Wild and cultivated lupins from the Tropics to the Poles. Proceedings of the 10th International Lupin Conference, Laugarvatn, Iceland, 19–24 June 2002. p. 206–207.
- Rosén, K. & Lundmark-Thelin, A. 1986. Hyggesbruket och markvården. Sveriges Lantbruksuniversitet. Skogsfakta Konferens 9. p. 42–49. (In Swedish).
- Savill, P., Evans, J., Auclair, D. & Falck, J. 1997. *Plantation silviculture in Europe*. 297 p. ISBN 0-19-854908-3.
- Smethurst, P.J., Turvey, N.D & Attiwill, P.M. 1986. Effect of *Lupinus* spp. on soil nutrient availability and the growth of *Pinus radiata* D. Don seedlings on a sandy podzol in Victoria, Australia. *Plant and Soil* 95: 183–190.
- Söderström, V., Bäcke, J., Byfalk, R. & Jonsson, C. 1978. Comparison between planting in mineral soil heaps and after some other soil treatment methods. Skogshögskolan, Dept. of Silviculture. Rapporter och Uppsatser 11. (In Swedish with English summary).
- Sprent, J.I. & Sprent, P. 1990. Nitrogen fixing organisms: pure and applied aspects. Chapman and Hall, London. 256 p.
- Sutton, R.F. 1993. Mounding site preparation: A review of European and North American experience. *New Forests* 7: 151–192.
- Tamm, C.O. 1947. Soil-improving measures tried on a poor site. *Meddelanden från Statens skogsforskningsinstitut* 36(7). 115 p. (In Swedish with English summary).
- 1991. Nitrogen in terrestrial ecosystems: questions of productivity, vegetational changes, and ecosystem stability. *Ecological Studies* 81. ISBN 3-540-51807-X.
- Thompson, D. 1984. Plowing of forest soils. Forestry Commission, Leaflet 71. 23 p.
- Troedsson, T. & Nyqvist, N. 1973. Marklära och markvård. Stockholm, Almqvist & Wiksell. 402 p. ISBN 91-20-05544-7. (In Swedish).
- Wickström, R. 1981. Markberedningsaggregat 1981. Forskningsstiftelsen Skogsarbeten. Uppsala. Teknik 8. (In Swedish).
- Zar, J.H. 1999. *Biostatistical analysis*. Fourth edition. Prentice-Hall, Upper Saddle River, New Jersey. ISBN 0-13-081542-X.
- Zobel, B.J. & van Buijtenen, J.P. 1989. Wood variation – its causes and control. Springer-Verlag. 363 p. ISBN 3-540-50298-X.

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