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Wood quality and volume production in four 24-year-old provenance trials with *Pinus contorta*

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Abstract

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The objectives of this study are to describe how yield and quality of *Pinus contorta* vary with locality and provenance in Sweden. The differences between *Pinus contorta* and *Pinus sylvestris* are also described. The material comprises four trials in a provenance series assessed at an age of 24 years. Assessments were made of height, diameter, different branch traits, stem straightness, number of spike knots, basic density and fibre properties. A comparison was made of *Pinus sylvestris* with similar dimensions. Based on sectional measurements of felled trees, volume production was estimated for lodgepole pine.

There were large differences in volume production, stem form and quality among the four trials. To achieve a high volume production, site and soil evaluation and treatment are important.

There were large and significant differences among provenances for most traits evaluated. The best provenances were of a more southern origin at the southern trials, Remningstorp and Bogesund, when compared to the northern trial, Lövsåsen.

In comparison with *P. sylvestris* at the same dimensions a correct *P. contorta* source has thinner branches and a lower number of branches while fibre length is increased.

Lodgepole pine could in some areas of southern and central Sweden produce more than Scots pine and possibly with an improvement in wood quality.

Key words: provenance, variation, quality, volume production, site, Lodgepole pine, Scots pine.
ODC 232.12, 165.52

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Introduction

Today *Pinus contorta* Dougl. (lodgepole pine) is the third most important tree species in Sweden, measured in terms of annual planting area. Planting is mainly concentrated to the north of latitude 59°30′N although there are certain limitations to its use. South of this limit, planting is only permitted for research purposes.

The first plantations with lodgepole pine in Sweden worth mentioning were established in the late 1920s and early 1930s. When it became evident from these plantations that lodgepole pine had a tremendous potential for production, renewed interest in the species was shown, for example, by establishing experiments of various kinds in the late 1950s. The start of a large scale reforestation programme with lodgepole pine can be timed with the publication of Nellbeck (1969). Since that time the total area planted with lodgepole pine has increased to more than 300 000 hectares by the beginning of 1986. This represents about 1.4% of the total forest area, but locally the proportion is considerably larger.

During the past 15 years a large number of studies has been published considering the use of *Pinus contorta* in northern Sweden. Summaries of the present state of knowledge on provenance research are given by Lindgren (1983), on tree improvement by Fries (1987), on yield by Hägglund et al. (1979), on timber quality by Persson (1982) and Andersson (1987) and on seed production by Nilsson (1981).

Few studies have been published considering the use of lodgepole pine south of latitude 60°N in Sweden. Also, there are few results published on older material or where good experimental designs have been used.

The aim of the present study is to elucidate:

- How the production and quality of a well defined provenance varies with locality in Sweden.
- The variation between provenances at the same locality.
- Differences between *Pinus contorta* provenances and *Pinus sylvestris* of local origin.

The comparisons are carried out concerning volume production, wood density, fibre characteristics, branching habit and straightness. Special attention has been paid to comparisons between provenances used in the old plantations and the best provenances in the experiments, thus making possible a forecast of the probable output from the large-scale plantations of today.

Material and methods

Material and assessments

The material used in our study consists of a *Pinus contorta* provenance series planted in 1962. Four trials were used in this study; Kullsjö lada, Remningstorp (lat 58°28′N, long 13°37′E, alt 125 m asl), Grabbtorp, Bogesund (lat 59°26′N, long 18°11′E, alt 20 m asl), Siljansfors (lat 60°53′N, long 14°23′E, alt 240 m asl) and Lövsåsen (lat 63°03′N, long 14°41′E, alt 425 m asl) (Fig. 1). The series was established by the Danish forester Carl Bang, and is commonly referred to as the "Bang series".

All four trials were established after final felling of an older stand and are situated on glacial till. The Remningstorp trial is situated on the lower part of an even slope next to a birch covered bog. The Bogesund trial is situated on the upper part and top of a slope. At this location the variation in soil conditions (e.g. depth to the bedrock) is large. The Siljansfors trial is situated in the middle of a long slope. Site conditions vary, with ridges of mineral soil intermixed with areas with high groundwater level. The Lövsåsen trial is situated on the lower part of a slope. Small ridges and plains are intermingled. One frost pocket exists within the trial but plots situated there are not included in the analysis.

The material used comprised different provenances of lodgepole pine and local sources of Scots pine (*Pinus sylvestris* (L)). The origin of the material is presented in Table 1 and Figure 2.

At each trial three replications were established and in each replication the provenances used were planted in 12×16 tree plots. The spacing was 1.25×1.25 metres at Remningstorp and Bogesund and 1.50×1.50 metres at Siljansfors and Lövsåsen. Bare root seedlings (2+1) treated with insecticides were planted without prior soil scarification. All trials were fenced as a protection against roe deer and elk.

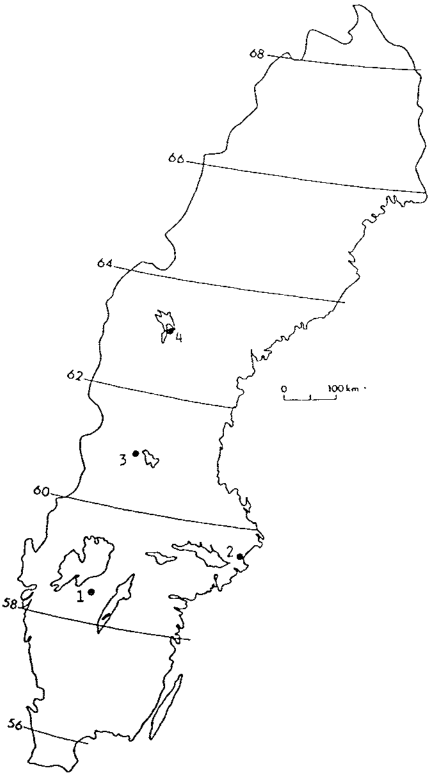


Fig. 1. Location of the four *P. contorta* provenance trials used in the study. 1. = Remningstorp, 2. = Bogesund, 3. = Siljansfors and 4. = Lövsåsen.

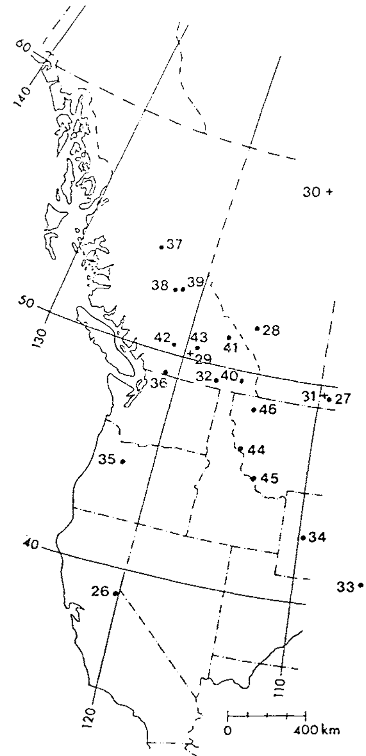


Fig. 2. Origin of *P. contorta* provenances used in the study. Provenances marked with + (29–31) are second generation landraces from forest district Tharandt, W. Germany.

Table 1. *Origin of provenances used in this study and trials where each provenance is used*

Lövs-åsen	Siljans-fors	Grabb-torp	Kullsjö lada		Lat. N	Long. W	m asl.
		X	X	26 Echo Summit, Cal.	38°49′	120°02′	2 300
X	X	X	X	27 Cypress Hills (A) Sask.	49°30′	109°30′	1 300
X	X	X	X	28 Calgary, Alta.	52°08′	115°24′	1 350
X		X	X	29 Salmon Arm, Shuswap, B.C. (Tharandt)	50°15′	119°20′	490–530
		X		30 Peace River Distr. B.C. (Tharandt)	59°	112°	400
		X		31 Cypress Hills (B) Sask. (Tharandt)	49°40′	109°50′	1 145
	X	X		32 Nelson, B.C.	49°29′	117°21′	1 400
			X	33 Medicine Bow, Wyo.	41°06′	106°11′	2 000
X	X	X	X	34 Shoshone, Wyo.	43°39′	109°56′	2 600
X	X	X	X	35 Cascadia, Ore.	44°25′	122°40′	1 300
X	X	X		36 Manning Park B.C.	49°15′	120°50′	300
X	X	X	X	37 Lake Stuart, Ft. St. James, B.C.	54°30′	124°15′	500–650
X	X	X	X	38 Quesnel, B.C.	53°02′	122°12′	800
X	X	X		39 Bowron Lake, B.C.	53°15′	121°25′	1 000
X	X	X	X	40 Fort Steele, B.C.	49°40′	115°36′	1 250
X		X		41 Donald, B.C.	51°31′	117°13′	850
X	X	X	X	42 Greenstone Mt. Kamloops, B.C.	50°36′	120°39′	1 750
X	X	X	X	43 Mount Ida, B.C.	50°39′	119°17′	1 250
	X	X		44 Lochsa, Montana	46°30′	114°45′	1 400
X	X	X	X	45 Wisdom, Montana	45°45′	113°45′	2 200
X	X	X	X	46 Whitefish, Montana	48°30′	114°30′	1 000
		X		47 Egsmark, Jylland			
		X	X	48 Thorup, Jylland			
		X		51 Håliden, Kopparbergs county			
X	X		X	99 Pinus sylvestris, local seed source			

Nos. 29–31 are second generation landraces from Tharandt forest district, W. Germany.

The four trials were assessed at age 24 years. On each plot the central 8×8 trees were assessed, while some of the trees outside the central plot were used in sampling for destructive tests. Assessments were made of height (dm), diameter at breast height (mm), bark thickness (mm), height to first live branch (dm) and the diameter of the thickest branch in the section between 1–2 metres height (mm). The number of branches thicker than one centimetre over bark in the section between 1–2 metres height was counted. Stem straightness between 0.5 and 5 metres height was estimated in five classes related to future utilisation of the bottom log. Class one represents a totally straight bottom log, while class five represents a bottom log unfit for future use as saw timber. The exclusion of the lower most part was based on the assumption that most bends at this level have an environmental rather than genetic cause. The number of spike knots from zero to five metres height was also recorded.

When thinning was carried out, ten trees from each plot, mainly taken outside the central 8×8 trees, were used for wood studies. A 200 mm thick disk was taken at breast height and used for determination of basic density and fibre properties. The sample of trees was made in order to achieve a good estimate of the trees remaining in the central 8×8 plot after thinning. A sampling aiming at the same mean value was made for *Pinus sylvestris*. Sixty trees with similar dimensions were sampled close to the site of each trial. The Scots pine samples at Lövsåsen and Siljansfors consist of trees sampled in the Scots pine plots within the trial and in the border rows of the trial. At Bogesund the local provenance in a Scots pine provenance trial was used. The Scots pine trial was situated five kilometres from the lodgepole pine trial, on abandoned farmland. At Remningstorp the sample was chosen from three provenances of neighbouring, nearly local, origin in a Scots pine provenance trial. The Scots pine trial was situated three kilometres from the lodgepole pine trial, on abandoned farmland.

The sample of trees used for determining wood quality in lodgepole pine was also sectioned for volume estimation. The five provenances with the highest volume production were identified in Remningstorp, Bogesund and Lövsåsen. On each plot where the five provenances were planted, the ten trees used for wood sampling were also used for sectioning. In all, 150 trees were used for sectioning at each trial. Furthermore, one provenance at Ekhagen, another provenance trial at Remningstorp, was used for sectioning. Details and results from the sectioning are given in Appendix.

Fibre dimensions were studied using the method described by Ståhl (unpublished). Fibre length and fibre thickness were studied on one increment core from each sample tree. Latewood from the fifth growth ring from the bark was used. After fibre separation, the length of 25 fibres and the thickness of ten fibres was assessed using a measurement micrometer.

Basic density was studied using the mercury immersion method described by Ericson (1959). Two samples were extracted from the fourth, fifth and sixth growth ring from the bark. After determination of dry weight, the volume of mercury displaced by each sample was measured.

Statistical methods

The calculations of stem volume and volume per hectare are based on the functions given by Näslund (1941, 1947) and Andersson (1954) for Scots pine. Values for volume of lodgepole pine are based on volume functions derived from data after stem sectioning (Appendix, model 2). In the Siljansfors trial, no sectioning of felled sample trees was performed. The volume functions for the Lövsåsen material were used here instead. The reason for using new functions was that existing functions describing stem volume of lodgepole pine are largely based on poorly known provenance material.

At the provenance level, the values of stem straightness and number of spike knots were transformed before statistical analysis. Stem straightness was transformed to per cent straight trees (the sum of the percentages of trees in stem straightness classes 1 and 2). Number of spike knots was transformed to per cent trees without spike knots.

Statistical analyses were performed using a standard program, SISS (Öberg, S. 1985, SISS – Swedish Interactive Statistical System). The following analyses were made: Two-way variance analyses, correlation analyses for provenance means, partial correlation analyses for single trees with elimination of provenance differences, and stepwise regression analyses. In the regression analyses, the dependent variables used were height, stem volume per hectare at Remningstorp, Bogesund and Lövsåsen. Furthermore, basic density was studied at Remningstorp and Lövsåsen. The model used was

$$y = k_1 + k_2\Delta LA + k_3\Delta LO + k_4\Delta LA^2 + k_5\Delta LO^2 + k_6\Delta LA\,\Delta LO$$

The independent variables used were latitude and longitude, squared latitude and longitude and the product of latitude and longitude. In all cases 40° was subtracted from the latitude ($\Delta LA = LAT - 40°$), while the longitude was subtracted from longitude 100° ($\Delta LO = 100° - LON$).

The method used for graphical description of the regression analyses is in principle the same as that described by Kung & Clausen (1984) and Prescher (1986).

In this study the following notations are used to indicate significance levels

★ significant at the 5 per cent level
★★ significant at the 1 per cent level
★★★ significant at the 0.1 per cent level

Traits assessed, their abbreviation and units used, are presented in Table 2.

Provenance and plot mean values for all four trials can be ordered from the Department of Forest Yield Research.

Table 2. *Traits assessed, their abbreviation and units used*

Trait	Abbreviation	Unit
Height (arithmetic mean)	H	dm
Diameter (arithmetic mean) at breast height	DBH	mm
Height to first live branch	HBR	dm
Volume per stem (bark included)	VST	dm^3
Volume per hectare (bark included)	VHA	m^3
Diameter of thickest branch (spike knots not included) between 1 and 2 m section	DBR	mm
Diameter of thickest branch (as above) in percentage of the diameter at breast height	DBR %	%
Number of branches thicker than 10 mm over bark between 1 to 2 m section (spike knots not included)	SBR	–
Straightness (from 0.5 to 4 m) in five classes (where 1 corresponds to totally straight stem while 5 corresponds to not usable as sawtimber)	STR	–
The percentage of the trees in stem straightness class 1+2	STR %	%
Number of spike knots (from 0 to 5 m) per tree	SPK	–
The percentage of trees without spike knots	NSPK %	%
Fibre diameter (arithmetic mean of 10 fibres) in growth ring five numbered from bark	FID	mm
Fibre length (arithmetic mean of 25 fibres) in growth ring five numbered from bark	FIL	mm
Basic density (mean of two samples in growth ring 4–6 numbered from bark)	BD	g/cm^3 (g/dm^3)[a]

[a] Only used in regression analyses and contour plots.

Results

Mean values and standard deviation of means for different traits are given for the four trials (Table 3). It is worth noting that the southernmost trial, Remningstorp, combines a good volume production with comparably good wood quality.

Two-way analyses of variance (Table 4) indicate few cases of significant variation between replications, the exceptions being fibre dimensions and basic density. Provenance variation was significant for all traits at Remningstorp and the majority of traits at Lövsåsen. Volume-related traits and basic density were also significant at Bogesund. At Siljansfors significant provenance variation was found for height only. Based on these results, no further analyses were carried out on the results from the Siljansfors trial.

The effect of provenance origin on wood quality and production was studied using the regression equations from Table 5 and transforming these to

Table 3. *Mean values ($\bar{X}$) and standard deviation (s) based on plot mean values for different traits for four P. contorta trials*

	Remningstorp		Bogesund		Siljansfors		Lövsåsen	
Trait	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*	$\bar{X}$	*s*
H	79.4	12.5	73.9	13.4	45.0	11.2	62.0	9.4
DBH	106.0	11.1	91.9	15.4	49.8	11.4	91.9	12.2
VST	42.8	12.1	30.7	11.9	8.2	4.8	27.7	8.0
VHA	91.5	24.7	83.9	38.4	29.6	17.5	63.7	32.6
HBR	22.6	6.5	19.2	6.9	8.6	2.4	14.5	5.0
DBR	18.0	3.3	21.9	4.4	10.1	1.6	20.6	5.5
DBR %	17.3	3.4	24.1	4.2	20.4	2.2	23.0	5.1
SBR	9.9	2.3	11.1	4.1	3.6	1.6	9.6	2.0
STR %	48.7	20.7	17.7	12.2	41.8	21.8	38.5	15.9
NSPK %	52.5	20.7	12.2	11.1	77.4	12.1	58.5	15.2
FID [a]	0.036	0.003	0.031	0.002	0.031	0.003	0.038	0.004
FIL [a]	2.23	0.25	2.31	0.34	1.92	0.15	1.94	0.22
BD [a]	0.339	0.020	0.320	0.012	0.336	0.010	0.293	0.013

[a] Based on mean of sampled trees.

Table 4. *Two-way analyses of variance. F-ratios for provenances and replications, test of significance and degrees of freedom for different traits in four trials*

	Remningstorp		Bogesund		Siljansfors		Lövsåsen	
	rep.	prov.	rep.	prov.	rep.	prov.	rep.	prov.
Trait	*df*=2	*df*=14	*df*=2	*df*=22	*df*=2	*df*=14	*df*=2	*df*=11
H	0.10	32.70**	7.31**	5.21**	0.32	2.32*	0.00	10.32**
DBH	0.09	5.82**	0.81	3.28**	0.11	1.82	1.85	2.18
VST	0.11	16.08**	2.15	5.05**	0.54	2.14	0.57	4.61**
VHA	1.04	10.02**	1.43	1.83*	0.17	1.63	0.77	17.78**
HBR	1.91	3.54**	2.34	1.25	0.37	1.19	3.10	7.86**
DBR	1.67	4.64**	2.50	0.94	0.80	1.83	7.94**	7.14**
DBR %	1.80	8.01**	6.03**	1.78*	1.67	1.21	2.81	9.28**
SBR	0.64	7.80**	4.70*	1.21	5.27*	1.97	7.58**	0.80
STR %	2.04	4.01**	6.35**	0.97	0.77	1.67	0.67	2.26*
NSPK %	1.01	4.26**	0.64	0.34	2.40	1.24	3.15	0.85
FID	35.25**	2.47*	3.93*	1.41	1.85	0.65	2.05	1.89
FIL	87.22**	6.39**	44.05**	3.66**	0.80	2.44*	3.16	5.94**
BD	6.70**	13.23**	0.02	1.36	14.66**	1.17	11.49**	7.54**

Table 5. *Transfer functions* ($y=k_1+k_2\times\Delta LA+k_3\times\Delta LO+k_4\times\Delta LA^2+k_5\times\Delta LO^2+k_6\times\Delta LA\Delta LO$) *for height (H), volume/stem (VST), volume/hectare (VHA) and basic density (BD) at three trials, and percentage of straight stems (STR %) and percentage trees without spike knots (NSPK %) at Remningstorp* (ΔLA=LAT-40, ΔLO=100-LON)

Dependent variables y		k_1	k_2	k_3	k_4	k_5	k_6	R
Remningstorp								
H	(dm)	58.4	3.27	–	−0.244	–	−0.104	0.87
VST	(dm^3)	26.3	2.11	–	−0.184	–	−0.102	0.79
VHA	(m^3)	63.6	3.64	–	−0.602	–	−0.361	0.81
BD	(g/dm^3)	260.1	–	−9.17	–	−0.215	0.088	0.76
STR	%	43.3	–	–	−0.476	−0.059	−0.464	0.79
BSPK	%	25.9	4.20	–	−0.295	–	−0.124	0.65
Bogesund								
H	(dm)	47.9	4.96	–	−0.205	–	–	0.41
VST	(dm^3)	2.8	3.38	−0.64	−0.143	–	–	0.53
VHA	(m^3)	27.4	11.59	–	−0.518	–	–	0.48
BD	g/dm^3	380.4	−12.61	–	0.575	–	–	0.80
Lövsåsen								
H	(dm)	74.3	–	2.44	−0.213	–	−0.298	0.80
VST	(dm^3)	22.3	3.48	1.68	−0.347	–	−0.208	0.70
VHA	(m^3)	245.8	−11.38	20.90	–	0.425	−0.862	0.82
BD	g/dm^3	248.9	–	−4.64	0.408	–	0.441	0.64

contour plots. Contour plots, with latitude and longitude as independent variables, are given for height (Figs. 3–5), stem volume (Figs. 6–8) and volume per hectare (Figs. 9–11) at Remningstorp, Bogesund and Lövåsen. Basic density was studied at Remingstorp (Fig. 12) and Lövsåsen (Fig. 13). Furthermore, the percentage of trees with straight stems (Fig. 14) and the percentage of trees without spike knots (Fig. 15) was studied at Remningstorp. The variation in stem form of provenances at different trials is presented in Appendix.

To describe the relationship between different

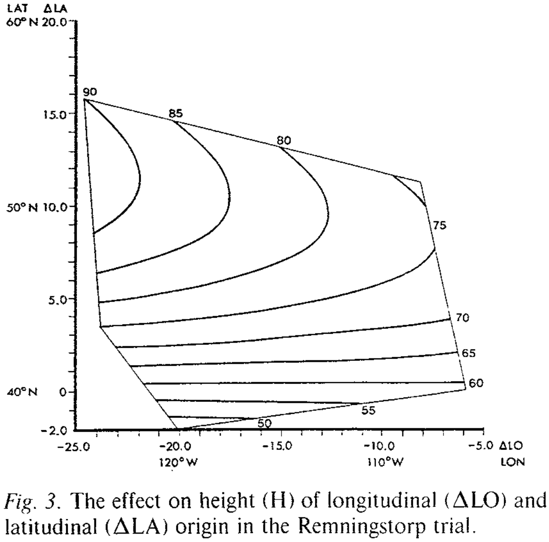


Fig. 3. The effect on height (H) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

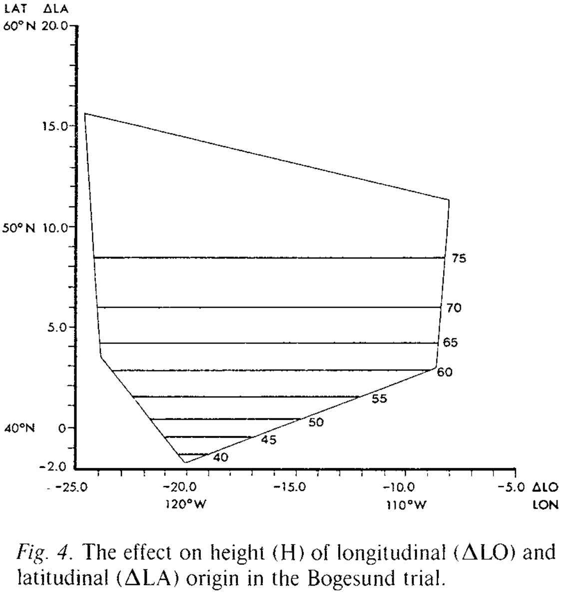


Fig. 4. The effect on height (H) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Bogesund trial.

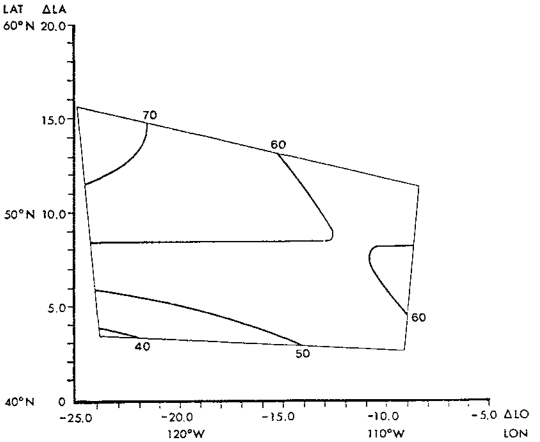


Fig. 5. The effect on height (H) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Lövsåsen trial.

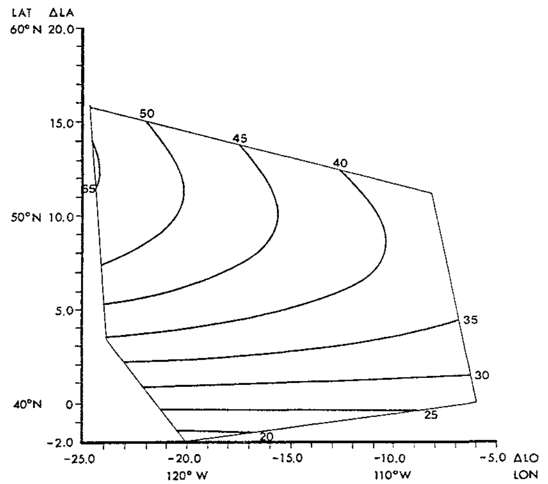


Fig. 6. The effect on stem volume (VST) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

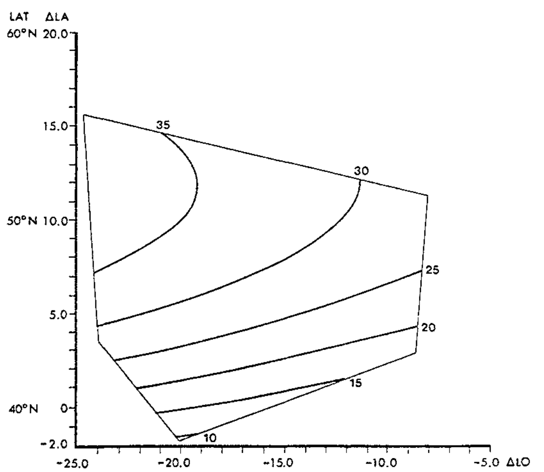


Fig. 7. The effect on stem volume (VST) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Bogesund trial.

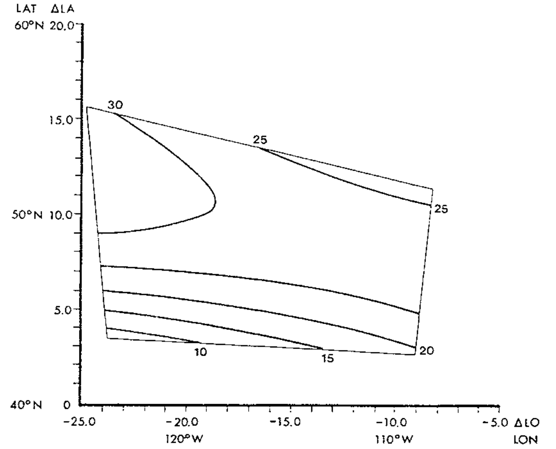


Fig. 8. The effect on stem volume (VST) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Lövsåsen trial.

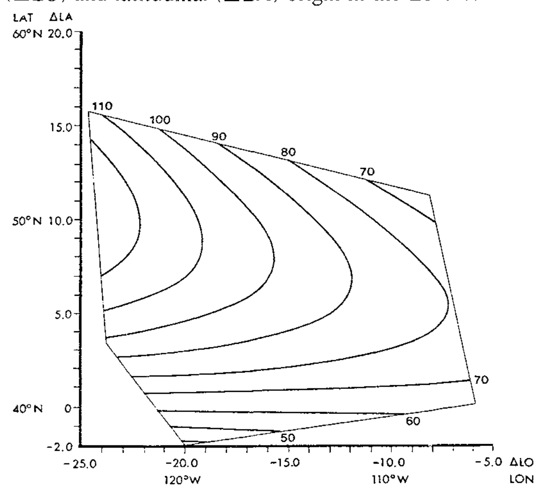


Fig. 9. The effect on volume per hectare (VHA) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

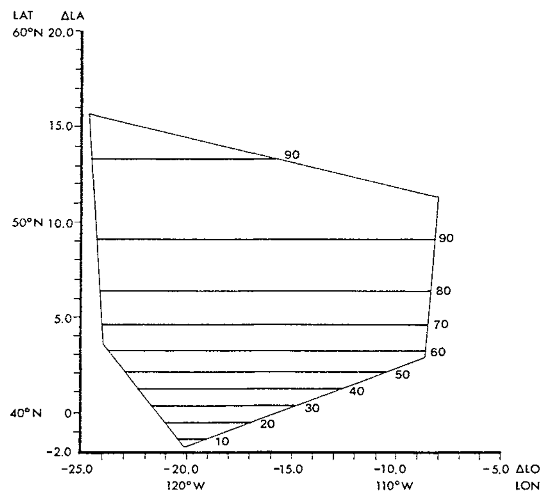


Fig. 10. The effect on volume per hectare (VHA) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Bogesund trial.

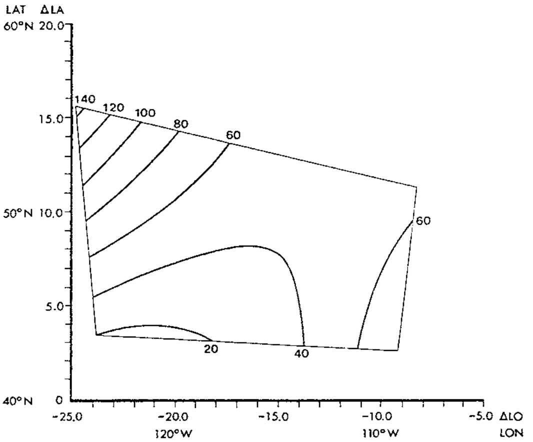


Fig. 11. The effect on volume per hectare (VHA) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Lövsåsen trial.

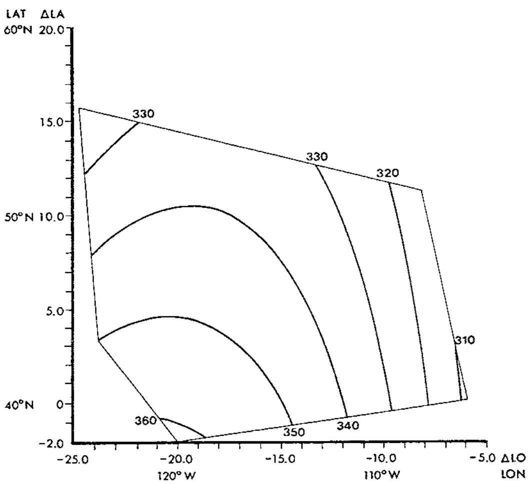


Fig. 12. The effect on basic density (BD) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

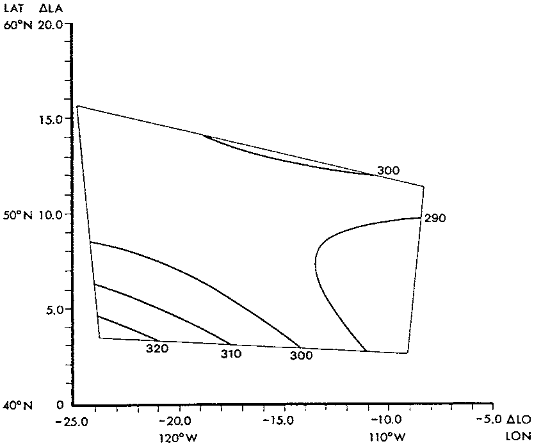


Fig. 13. The effect on basic density (BD) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Lövsåsen trial.

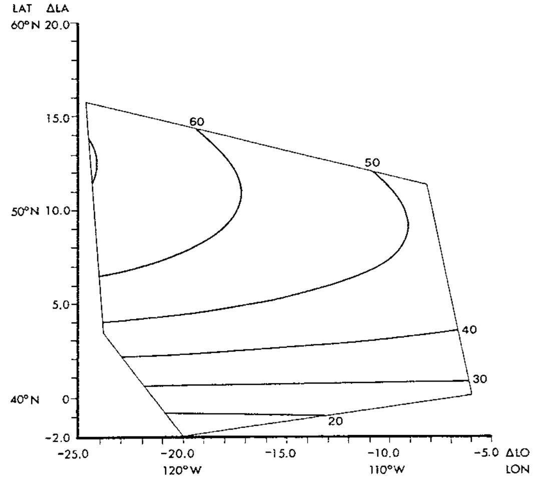


Fig. 14. The effect on percentage of trees with straight stems (STR, %) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

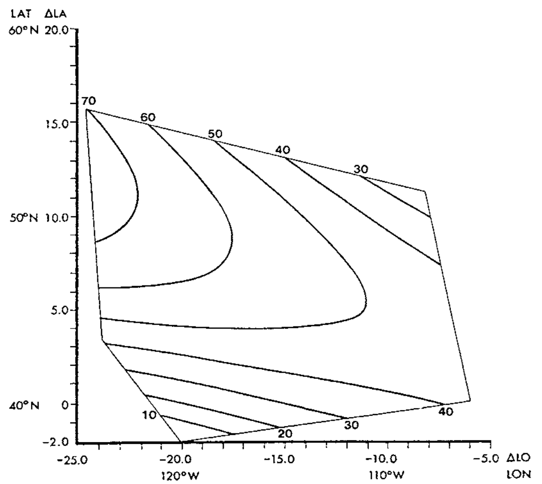


Fig. 15. The effect on percentage of trees without spike knots (NSPK, %) of longitudinal (ΔLO) and latitudinal (ΔLA) origin in the Remningstorp trial.

traits, two types of correlation are presented for each of the three trials; correlations based on provenance mean values, and partial correlations for individual trees, (provenance differences eliminated). The correlation matrices for mean values are given in Tables 6 to 8 and the partial correlations for individual trees in Tables 9 to 11 for Remningstorp, Bogesund and Lövsåsen, respectively.

A comparison was made of one northern and one southern group of lodgepole pine provenances with Scots pine of the same dimensions. The northern group represents the highest producing provenances in this study, while the southern group represent provenances used in older studies of quality. In Table 12 the mean values for different groups are presented.

Table 6. *Correlation coefficients based on provenance mean values for different traits in the Remningstorp trial (n=15)*

Trait	DBH	H	VST	VHA	HBR	STR, %	NSPK, %	DBR, %	SBR	DBR, %	FID	FIL
H	0.763***											
VST	0.919***	0.941***										
VHA	0.639*	0.834***	0.789***									
HBR	0.527*	0.640*	0.638*	0.852***								
STR, %	0.287	0.600*	0.478	0.685**	0.513							
NSPK, %	0.233	0.741**	0.514*	0.738**	0.578*	0.682**						
DBR	0.070	−0.496	−0.239	−0.603*	−0.455	−0.571*	−0.834***					
SBR	−0.171	−0.727**	−0.495	−0.763***	−0.564*	−0.746**	−0.922***	0.908***				
DBR, %	−0.574*	−0.822***	−0.758**	−0.883***	−0.668**	−0.637*	−0.836***	0.768***	0.843***			
FID	0.284	0.629*	0.490	0.475	0.298	0.558*	−0.500	−0.312	−0.578*	−0.449		
FIL	0.583*	0.889***	0.772***	0.640*	0.453	0.556*	−0.704**	−0.466	−0.681**	−0.765***	0.798***	
BD	0.053	−0.019	−0.005	−0.355	−0.382	−0.346	−0.210	0.027	0.194	−0.038	−0.202	0.077

Table 7. *Correlation coefficients based on provenance mean values for different traits in the Bogesund trial (n=23)*

Trait	DBH	H	VST	VHA	HBR	STR, %	NSPK, %	DBR, %	SBR	DBR, %	FID	FIL
H	0.854***											
VST	0.976***	0.912***										
VHA	0.628**	0.844***	0.693***									
HBR	0.464*	0.708***	0.513*	0.850***								
STR, %	0.398	0.504*	0.456*	0.654***	0.379							
NSPK, %	0.409	0.536**	0.427*	0.357	0.466*	0.203						
DBR	0.605**	0.279	0.488*	−0.043	−0.199	−0.182	−0.002					
SBR	0.407	0.486*	0.420*	0.418*	−0.343	0.389	−0.535**	0.151				
DBR, %	−0.580**	−0.716***	−0.653***	−0.764***	−0.709***	−0.657***	−0.484*	0.277	−0.284			
FID	0.703***	0.807***	−0.758***	0.695***	0.549**	0.455*	0.228	0.283	0.501*	−0.507*		
FIL	0.557**	0.764***	0.656***	0.640**	0.580**	0.413	0.302	0.130	0.519*	−0.488*	0.802***	
BD	−0.551**	−0.684***	−0.547**	−0.601**	−0.451*	−0.359	−0.355	−0.319	−0.299	0.399	−0.641***	−0.519*

Table 8. *Correlation coefficients based on provenance mean values for different traits in the Lövsåsen trial (n=15)*

Trait	DBH	H	VST	VHA	HBR	STR, %	NSPK, %	DBR, %	SBR	DBR, %	FID	FIL
H	0.595*											
VST	0.920***	0.828***										
VHA	0.092	0.796**	0.403									
HBR	−0.131	0.580*	0.143	0.920***								
STR, %	−0.002	0.108	0.284	0.242	0.259							
NSPK, %	0.063	0.207	0.004	0.183	−0.022	0.574*						
DBR	0.531	−0.237	−0.203	−0.703**	−0.805***	−0.499	−0.273					
SBR	0.359	−0.479	0.004	−0.705**	−0.605*	0.109	−0.099	0.642*				
DBR, %	0.007	−0.605*	−0.203	−0.860***	−0.860***	−0.637*	−0.394	0.843***	0.466			
FID	0.276	0.751**	0.532	0.724**	0.500*	−0.191	0.081	−0.234	−0.601*	−0.429		
FIL	0.382	0.838***	0.601*	0.756**	0.638*	−0.051	0.108	−0.234	−0.535	−0.508	0.921***	
BD	−0.204	−0.418	−0.331	−0.308	−0.204	0.179	−0.125	0.068	0.194	0.149	−0.367	−0.386

Table 9. *Partial correlation coefficients based on single-tree values, eliminating the provenance differences for different traits in the Remningstorp trial (n >950)*

Trait	DBH	H	VST	HBR	STR	SPK	DBR	SBR
H	0.724***							
VST	0.944***	0.784***						
HBR	0.051	0.335***	0.085**					
STR	−0.203***	−0.270***	−0.227***	−0.175***				
SPK	−0.227***	−0.349***	−0.255***	−0.239***	0.372***			
DBR	0.603***	0.284***	0.528***	−0.270***	0.062*	0.026		
SBR	0.600***	0.366***	0.516***	−0.100**	0.000	−0.069*	0.607***	
DBR, %	−0.241***	−0.379***	−0.210***	−0.378***	0.255***	0.240***	0.562***	0.132***

Table 10. *Partial correlation coefficients based on single-tree values, eliminating the provenance differences for different traits in the Bogesund trial (n >1 480)*

Trait	DBH	H	VST	HBR	STR	SPK	DBR	SBR
H	0.716***							
VST	0.944***	0.751***						
HBR	0.026	0.444***	0.083**					
STR	−0.043	−0.232***	−0.110***	−0.200***				
SPK	−0.033	−0.092**	−0.080*	−0.098***	0.223***			
DBR	0.615***	0.252***	0.486***	−0.312***	0.124***	0.111***		
SBR	0.086**	0.070*	0.068*	0.023	0.014	0.023	0.089**	
DBR, %	−0.050	−0.211***	−0.147***	−0.335***	0.161***	0.175***	0.672*	0.044

Table 11. *Partial correlation coefficients based on single-tree values, eliminating the provenance differences for different traits in the Lövsåsen trial (n >1 060)*

Trait	DBR	H	VST	HBR	STR	SPK	DBR	SBR
H	0.784***							
VST	0.946***	0.805***						
HBR	0.079*	0.362***	0.102***					
STR	−0.325**	−0.434***	−0.332***	−0.110***				
SPK	−0.024	−0.163***	−0.063**	−0.102***	0.393***			
DBR	0.711***	0.408***	0.638***	−0.213***	−0.101***	0.128***		
SBR	0.726***	0.477***	0.629***	−0.103***	−0.170***	0.048	0.667***	
DBR, %	−0.213***	−0.371***	−0.205***	−0.348***	0.205***	0.189***	0.429***	0.062*

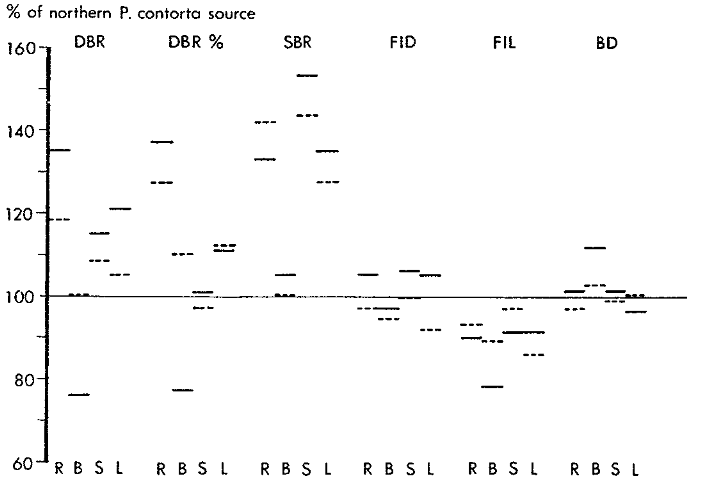
Table 12. *Mean values of different traits for two southern lodgepole pine provenances (27+28=S) and three northern lodgepole pine provenances (37+38+42=N) in comparison with Scots pine provenances (PS) from local provenances. Mean values of trees sampled for destructive tests*

Site. . .	Remningstorp			Bogesund			Siljansfors			Lövsåsen		
	S	N	PS	S	N	PS	S	N	PS	S	N	PS
Trait												
DBH	119	125	124	94	106	104	76	70	79	99	104	112
H	81	93	88	74	75	84	61	64	63	66	79	64
VST	51	63	57	30	39	47	18	17	20	30	38	37
HBR	20	27	36	19	18	39	11	13	15	15	22	15
DBR	20	17	23	25	25	19	14	13	15	20	19	23
SBR	14.2	10.0	13.3	12.3	12.3	12.9	7.3	5.1	7.8	12.8	10.1	13.6
DBR, %	17.6	13.9	19.0	26.5	24.1	18.6	18.3	18.8	18.9	20.6	18.4	20.5
FID	0.036	0.037	0.039	0.030	0.032	0.031	0.031	0.031	0.033	0.036	0.039	0.041
FIL	2.17	2.34	2.10	2.15	2.40	1.87	1.95	2.00	1.83	1.84	2.13	1.94
BD	0.324	0.334	0.337	0.316	0.311	0.350	0.331	0.334	0.337	0.294	0.294	0.284

In Figure 16 the relative values of the southern lodgepole pine sources and the Scots pine sources are presented, the northern lodgepole pine sources used as a reference.

The deviation from provenance means in diameter after thinning is presented for the sample trees in Figure 17. It is worth noting that the sample on the average has a higher mean diameter then the provenance mean after thinning.

Fig. 16. Relative values (%) of branch diameter, number of branches, fibre length, fibre diameter and basic density for southern sources of *P. contorta* (27, 28) and local sources of *P. sylvestris*. Northern sources of *P. contorta* are used as reference value (37, 38, 42 = 100%). R = Remningstorp, B = Bogesund, S = Siljansfors and L = Lövsåsen.
—— *P. sylvestris*
– – – *P. contorta* southern source



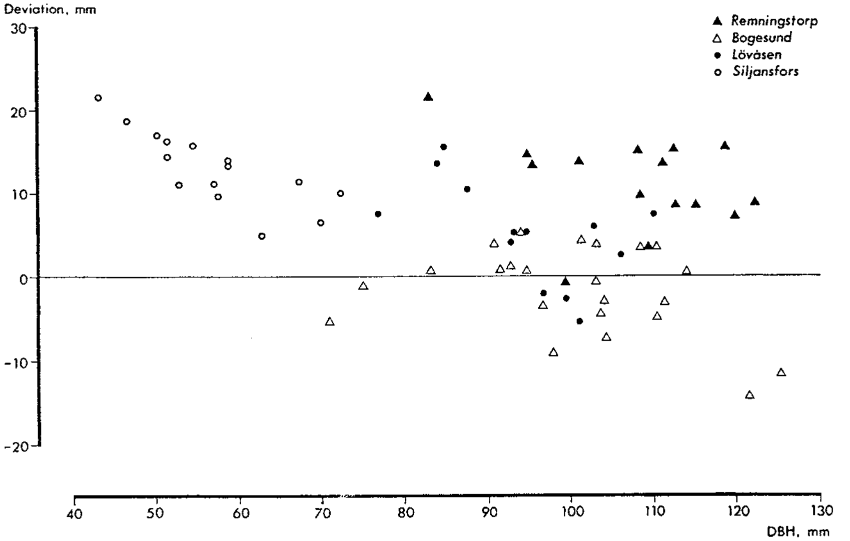


Fig. 17. Deviation (mm) of sample tree diameter in comparison with provenance mean diameter (DBH) after thinning.

Discussion

Site and soil variation

There were large differences in volume production and quality (Table 3) and in stem form (Appendix) between the four trials in this study. These differences seemed to be related to variations in site quality and soil conditions. For the two successful trials, Lövsåsen and Remningstorp, there was also an indication of differences between northern and southern sites. Of the four trials, two are situated on heterogeneous sites. One of those, Siljansfors, revealed no significant differences between replications or between provenances. The site is variable, with wet areas interrupted by ridges with good productive capacity. At the other heterogeneous site, Bogesund, some traits showed significant provenance differences. The large variation in soil depth, and early attacks of fungi and insects, limited the value of this trial. At the northern trial, Lövsåsen, early attacks by voles and the effect of at frost-prone depression in the central part of the trial, affected the results. Since the rest of the trial is homogeneous, Lövsåsen is considered to be of great interest, hence only the damaged areas have been eliminated. The southern trial, Remningstorp, is homogeneous and without any substantial damage. The conclusions drawn from this study are therefore based on the results from Remningstorp and Lövsåsen, while support is given from the Bogesund trial.

To summarise, of four trials two showed considerable environmental heterogeneity, with a large effect on the evaluation, while the third was heterogeneous to a minor extent. All these sites were selected by skilled technicians with long experience in the establishment and evaluation of field trials. In spite of this, the heterogeneity seems to have affected estimates of provenance means and variation, at least in the Siljansfors and the Bogesund trials, while at Lövsåsen, individual plots have been omitted. Although provenance differences were large for most traits, they are small in relation to the environmental effects caused by soil and site variation within a heterogeneous replication.

Provenance variation

There were large and significant differences between provenances in volume-related traits (Table 4). The same could be said about quality-related traits, although exceptions exist, mainly in the Bogesund trial. Thus the selection of provenance material is of major importance for future wood quality and production.

In the southern trials, Remningstorp and Bogesund, the optimum latitude for volume production seems to have been reached. It must be noted, however, that the area of origin suggested to be the best for reforestation in a large part of northern Sweden (Ft. St. John, cf. Lindgren 1983), is not represented in this series. For height (Fig. 3 and 4), stem volume (Fig. 6 and 7) and volume/hectare (Fig. 9 and 10) an optimum value is reached for latitude in the functions. However, in the Lövsåsen trial the optimum value of the function is not reached for height (Fig. 5) or volume/hectare (Fig. 11). The results correspond well with present transfer recommendations for northern Sweden, as the seed sources recommended are more northern than the material used in our study. Considering the longitudinal variation, more western seed sources than those tested in this series seem to be of interest in Sweden.

The percentages of straight stems and stems without spike knots for different provenances at Remningstorp are presented in Figures 14 and 15. It is interesting to note that the provenances with the highest volume production are also those with the highest percentage of straight stems and stems without spike knots in this trial. The same pattern was recognized at Bogesund, while no such obvious relationship could be detected at Lövsåsen.

Basic density in the Remningstorp (Fig. 12) and Lövsåsen (Fig. 13) trials formed a pattern deviating from those presented for other traits. Although a negative relationship exists with volume production, other factors also seem to regulate basic density.

The variation in stem form between the best producing provenances was small, and not significant (Appendix). There was good agreement between the estimates from an earlier volume function (Eriksson, 1973) and the newly-derived functions.

Relationship among traits

For all trials, the correlations of provenance mean values for height, diameter and volume/stem was strong and significant (Tables 6,7 and 8). In the Lövsåsen trial, the correlation of volume per hectare and diameter at breast height was low. This could probably be explained by large differences in mortality at a young age. Provenances with high mortality reacted by increased diameter growth of the surviving trees.

The percentages of straight trees and trees without spike knots were highest in the most productive provenances on all three sites, although correlations were not significant at Lövsåsen. These results contrast with the results obtained by Prescher & Ståhl (1986) for Scots pine in southern Sweden. The differences may be related to the transfer of the material. In both studies, northern provenances produced trees with straighter stems and fewer spike knots. In the lodgepole pine study, the highest volume production was also achieved by the most northern provenances used in the study. For the Scots pine provenances in southern Sweden, the highest volume production was often achieved by the local provenance or by provenances transferred from the south.

Branch diameter and number of branches decreased with increased height and volume/hectare at Remningstorp and Lövsåsen, while the correlation with diameter differed with site and trait. Relative branch diameter was negatively correlated with all volume-related traits at all three sites. Differences may be related to true source differences in branch habit, but also to differences caused by competitive effects. Furthermore, increased growth rate, i.e. taller trees, would by definition lead to decreased number of whorls per metre stem, if not compensated by extra whorls.

Fibre diameter and fibre length were positively and sometimes significantly correlated to volume-related traits. Basic density was negatively correlated to volume related traits, but significant correlations were obtained only at Bogesund.

When the relationship among traits for individual lodgepole pine trees was analysed after provenance differences had been eliminated (Tables 9, 10 and 11) the similarity of different trials was striking. In all trials, trees with a large volume were also straight and had few spike knots, the number of branches was high, branch diameter was high while relative branch diameter (branch diameter in relation to the tree diameter) was low. All this when compared to trees with a small volume within a provenance.

These results agreed closely with those found for Scots pine by Prescher & Ståhl (1986).

A comparison of lodgepole pine and Scots pine

The generally stated reason for the present large-scale use of lodgepole pine in Swedish forestry, is that since lodgepole pine attains a given size in a shorter time than Scots pine, the rotation may be shortened. Thus, in a fair comparison, the two pine species should be compared at the same dimensions. This causes considerable difficulties concerning experimental design. When the two species are even-aged, lodgepole pine has inevitably had the larger dimensions. The comparison within the experiment will be limited to yield after a certain period of time. Branch diameter, counts of number of branches per unit stem length and assessments of straightness could possibly also be compared at the same age for both species.

Such comparisons can only be carried out at the two northern sites, Lövsåsen and Siljansfors. At the two southern sites, the Scots pine is not comparable with the lodgepole pine. This is because of poor survival at initial planting and subsequent beeting of the Scots pine. This has resulted in the bulk of the Scots pine being about three years younger than the lodgepole pine.

The importance of comparable tree dimensions is most pronounced concerning wood properties, such as basic density and fibre dimensions. Many studies show that both these traits increase with increased maturity of the tree. Here the basis for a comparison must be Scots pine near the experiment, of local provenance and of approximately the same diameter as the lodgepole pine which has been used for wood studies. This means that the Scots pine will be older than the lodgepole pine.

A comparison of two different sources of lodgepole pine with Scots pine was made (Table 12 and Fig. 16). The material was chosen in order to find a local provenance of Scots pine with similar dimensions and on a site close to the trial. In this way the bias caused by differences in dimensions would be minimized, while still keeping site differences at a low level.

The Scots pine material in the two southern trials was sampled in a provenance trial. These provenances were older than the lodgepole pines sampled. In the two northern trials, the Scots pine was sampled among the biggest trees in the Scots pine plots and the border rows, utilizing the variation within the material. Thus, the Scots pine material sampled in the northern trials was of the same age but growing considerably faster than the average for that species.

From the results it seems clear that the choice of the northern lodgepole pine source had a very large, positive effect on branch traits as well as on fibre length. For fibre diameter and basic density, differences were small. Similarly, the northern lodgepole pine source had considerably better branch habit and fibre length than the local source of Scots pine. In fact, even the southern lodgepole pine source was as good as or better than the local source of Scots pine when branch traits or fibre length are compared. That lodgepole pine is also superior the Scots pine when the quality yield of sawn products is compared, was confirmed in a recent study (Boutelje & Brundin 1985), based on 55-year-old material originating close to the Remningstorp trial.

The results may seem to contradict the opinion commonly held about lodgepole pine in Sweden. In fact, planted lodgepole pine often has been compared with naturally regenerated Scots pine. Uusvaara (1974, 1985) has shown that planted Scots pine has considerably poorer quality than naturally regenerated pines, so it is evident that a fair comparison can only be made between planted trees. In addition, the spacing must be similar.

Implications for silviculture and forest tree improvement of lodgepole pine

The results of this study indicate that the introduction of lodgepole pine could affect silviculture and should affect forest tree improvement in south and central Sweden.

The relatively poor results achieved at the two trials Bogesund and Siljansfors are not an indication that lodgepole pine is a bad choice in central Sweden. Careful soil scarification, and, at Siljansfors, also improved drainage, would probably have decreased heterogeneity in these trials and made the future stand more even. At these sites, lodgepole pine has produced well in comparison with Scots pine of local origin. The lesson to learn from these trials is that local conditions have a major effect on forest yield and that the only true estimator of forest yield is a forest tree. The choice of a representative site for a trial is extremely difficult, and early evaluations may be misleading.

The forest tree breeder working with lodgepole pine in south and central Sweden is fortunate. At the provenance level, the positive correlations between volume yield and wood quality indicate that a good choice of provenance may improve volume production and wood quality, wood density being the exception.

A comparison of wood quality for lodgepole pine and Scots pine indicates substantial advantages for lodgepole pine. At the same dimensions, a correct source of lodgepole pine has better branch characteristics and longer fibres than Scots pine.

The results of this study are that a correct source of lodgepole pine would be a good alternative in some areas of southern and central Sweden. Lodgepole pine would yield more than Scots pine, possibly with an improvement in wood quality.

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Appendix

Tree volume functions for lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) differentiated by site and provenance

by Harry Eriksson

Volume of single trees was estimated by sectioning 150 felled trees of lodgepole pine on each of four investigation plots (cf. p. 5). On each experimental plot sample trees for sectioning were chosen from among those provenances which had given the highest yield on that site. Stem analysis was performed in the following way.

The diameters were calipered both at breast height and at 20 relative tree heights. The relative heights used were 1, 2, 4, 6, 10, 14, 18, 20, 25, 30, 40, 50, 60, 65, 70, 75, 80, 85, 90 and 95%. Double bark thickness was measured at the same levels of the stem as the diameters. Two measurements of bark thickness were made at right-angles to each other. Thus diameter under bark could be estimated, also the stem volume excluding bark.

The stem volume above stump was determined with the aid of the following numerical integration formula. Stump height was 1% of the tree height.

$$v=(d_{11}d_{12}k_1+d_{21}d_{22}k_2+d_{41}d_{42}k_4+\ldots+d_{951}d_{952}k_{95})\ \frac{h}{10^9},$$

where

v = stem volume above stump, dm^3

h = tree height above ground, cm

d_{11} = diameter of the tree at 1% of tree height, mm, first measurement

d_{12} = diameter of the tree at 1% of tree height, mm, second measurement at right-angles to the first measurement

k_1 = constant

d_{21} = diameter of the tree at 2% of tree height, mm, first measurement

d_{22} = diameter of the tree at 2% of tree height, mm, second measurement at right-angles to the first measurement

k_2 = constant

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d_{951} = diameter of the tree at 95% of tree height, mm, first measurement

d_{952} = diameter of the tree at 95% of tree height, mm, second measurement at right-angles to the first measurement

k_{95} = constant.

As the material is taken from young stands, there is little variation in diameter and tree height, as shown in the following table.

	Maximum value for	
Locality	DBH, cm	Tree height, m
Lövsåsen	14.2	10.3
Kullsjö lada	14.2	11.8
Ekhagen	12.4	11.3
Grabbtorp	16.0	11.5

In previous work, when deriving tree volume functions for single trees, a great number of different types of functions, variables and variable transformations have been used for smoothing either the stem volume directly or different tree form expressions indirectly (cf. Näslund, 1936, 1941, 1947: Hagberg &Matérn, 1975: Eriksson, 1973; Braastad, 1966; Laasasenaho, 1982; Varmola & Vuokila, 1986; Fog & Jensen, 1953; Olesen, 1976; Pollanschütz, 1966; Kennel 1969). Here a multiplicative model has been used for smoothing the stem volume above stump. The following alternative types of multiplicative model have been judged to be reasonable to use:

Model 1: $\ln v = a_0 + b_1 \ln d + b_2 \ln h$

Model 2: $\ln v = a_0 + b_3x_1 + b_4x_2 + b_5x_3 + b_1 \ln d + x$ $b_2 \ln h$

Model 3: $\ln v = a_0 + b_3x_1 + b_4x_2 + b_5x_3 + b_1 \ln d + b_6x_5 + b_7x_6 + b_8x_7 + b_9x_8 + b_{10}x_9 + b_2 \ln h$,

where

v = stem volume incl. or excl. bark, dm^3

d = diameter at breast height incl. or excl. bark, mm

h = tree height above ground, cm

x_1, x_2, x_3 = indicator variables for investigation site (dummy variables).

$x_5 \ldots x_9$ = indicator variables for provenance × ln d (dummy variables).

By regression analysis the following estimates of the parameters a and b are obtained. The standard error of the parameter estimates are given in parentheses.

There were 446 felled and stem analysed trees in the analysis. A small number of stems with forks were removed before the analysis.

Model 1

Incl. bark $\ln v = -11.3866 + 1.81911 \ln d + 0.97962 \ln h$
$(0.02132) \quad (0.02717)$

Excl. bark $\ln v = -11.6392 + 1.82852 \ln d + 1.00695 \ln h$
$(0.02122) \quad (0.02803)$

Model 2

Incl. bark $\ln v = a + 1.77189 \ln d + 0.097627 \ln h$
$(0.01989) \quad (0.02564)$

the value of constant a is for
Grabbtorp = −11.18481
Kullsjö lada = −11.10184
Ekhagen = −11.10900
Lövsåsen = −11.14193

Excl. bark $\ln v = a + 1.77723 \ln d + 0.99547 \ln h$
$(0.02032) \quad (0.02684)$

the value of constant a is for
Grabbtorp = −11.36124
Kullsjö lada = −11.28154
Ekhagen = −11.29044
Lövsåsen = −11.33154

Model 3

Incl. bark $\ln v = a + b \ln d + 0.98107 \ln h$
(0.02771)

the value of constant a is for
Grabbtorp = −11.2326
Kullsjö lada= −11.1539
Ekhagen = −11.2227
Lövsåsen = −11.1954

the value of parameter b is for provenance

No. 29 = 1.7784	No. 38 = 1.7773
No. 35 = 1.7701	No. 39 = 1.7815
No. 36 = 1.7740	No. 42 = 1.7727
No. 37 = 1.7771	No. 43 = 1.7774

Excl. bark $\ln v = a + b \ln d + 1.00231 \ln h$
(0.02888)

the value of constant a is for
Grabbtorp = −11.3974
Kullsjö lada = −11.3897
Ekhagen = −11.3449
Lövsåsen = −11.3721

the value of parameter b is for provenance

No. 29 = 1.7830	No. 38 = 7.7828
No. 35 = 1.7735	No. 39 = 1.7867
No. 36 = 1.7791	No. 42 = 1.7774
No. 37 = 1.7825	No. 43 = 1.7820

The differentation by different localities is adequate. The analysis shows that there are different volume levels on the different investigation plots for a certain combination of diameter and tree height values. If the level is determined in relative values, the following results are obtained according to model 2:

Locality	Incl. bark	Excl. bark
Grabbtorp	100	100
Kullsjö lada	108.7	108.3
Ekhagen	107.9	107.3
Lövsåsen	104.4	104.4

These differences in level were significant. The differences on stem form between the different localities were presumably caused by differences in soil properties and climate between the investigation plots. Survival may also have influenced the results. Differences in respect of spacing in the plantations, between the three southernmost plots and the northernmost plot, as well as differences in mortality in the experiment between the time of planting and the investigation, may be expected to have caused variations in the stem number between the localities. On the other hand, the analysis did not show any distinct differences in stem form between the different provenances tested here. The differences between provenances were very small (−0.7−+0.4%) and not significant.

For comparison of the estimates made by the tree volume functions derived here and those earlier used in Sweden (Eriksson, 1973), the volume estimates of some typical trees are shown in Table A1. One group of type trees represents extremely short trees with regard to DBH, and the other group, trees with normal height with regard to DBH.

The comparisons in Table A1 show that there was close agreement between the estimates made by the earlier used volume function (Eriksson, 1973) and the newly-derived functions. Only in the small dimensions did the new functions result in higher estimates of tree volume. There were differences in stem form

Table A1. *Tree volume incl. bark, dm^3, according to different volume functions for trees with different diameters at breast height and tree heights above ground*

Volume function and investigation plot	Diameter at breast height incl. bark, mm									
	50	75	100	125	150	50	75	100	125	150
	Tree height, dm									
	25	40	55	75	90	80	90	100	110	120
Model 1	3.12	10.35	23.86	48.51	80.81	9.76	22.90	42.85	70.60	107.11
Model 2										
Grabbtorp	3.12	10.12	22.99	46.22	76.28	9.71	22.34	41.22	67.18	101.02
Kullsjö lada	3.39	11.00	24.98	.50.22	82.88	10.55	24.27	44.78	72.99	109.76
Ekhagen	3.37	10.92	24.80	49.86	82.29	10.47	24.10	44.47	72.47	108.98
Lövsåsen	3.26	10.56	24.00	48.25	79.62	10.14	23.31	43.03	70.12	105.45
Eriksson (1973)	2.56	9.15	22.23	47.34	81.36	8.89	21.79	38.40	71.31	110.68

between the investigation plots represented in this study. These differences were not correlated with differences in provenance.

The tree volume functions presented here are only to be used for lodgepole pine trees with a DBH lower than 16 cm. The tree height may not exceed 12 m.