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Biomass Production of Dense Direct-Seeded Lodgepole Pine (*Pinus contorta*) at Short Rotation Periods

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Lodgepole pine (*Pinus contorta*) is a fast-growing species that is suitable for producing woody biomass in Nordic countries. Direct seeding of this species is cheaper than planting and creates dense, stable stands. The objective of this study was to quantify the stem volume and biomass production of direct seeded lodgepole pine stands grown under different site conditions with different stem densities, at an age that would permit extensive harvesting of biomass. A circle-plot inventory was performed in 16 of the oldest direct seeded lodgepole pine stands in mid-northern Sweden. Stemwood production of almost 200 m^3/ha was achieved on average on the best sites, rising to about 300 m^3/ha for the best circle-plots within 30 years of direct seeding despite the fact that pre-commercial thinning was made once or twice. This corresponds to 100 and 140 tons of dry weight biomass/ha, respectively. Higher stand stem densities (≥3000 st/ha) yielded more biomass with only slight reductions in diameter at breast height. The development of stem volume with respect to dominant height in direct seeded stands was becoming comparable to that in planted stands with similar spacing. It therefore seems that there is an unutilized potential for cost-effectively growing lodgepole pine in dense stands for biomass production after direct seeding. It may be possible to devise regimes for short(er) rotation forestry that would yield substantial amount of inexpensive biomass for biorefineries within a few decades.

Keywords *Pinus contorta*, lodgepole pine, biomass production, biorefinery, direct seeding, short rotation
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1 Introduction

Society's dependence on fossil fuels is currently a major environmental and political issue, and reducing this dependence will be a crucial step in creating a sustainable industrial society and will present challenges for silviculture and forestry (FitzPatrick et al. 2010, Schoene and Bernier 2012). There are two ways in which consumption could potentially be made sustainable: dematerialisation (i.e. reducing the quantity of resources consumed per person) and transmaterialisation (i.e. finding sustainable alternatives to important raw materials and energy sources) (Clark and Deswarte 2008). Considerable effort has been invested into identifying substitutes for oil and a wide range of biomass feedstocks have been considered, including byproducts generated by agriculture and the food industry. Forest biomass is a particularly appealing (and potentially general) substitute in certain countries that have extensive forest cover such as Sweden and Finland (Mattsson-Turku 2007, Höjer and Hedeklint 2011).

Forest biomass is a potentially useful raw material for the production of biofuels as well as valuable bio-based substances such as chemicals (Amidon and Liu 2009). Tall oil is an extractive of pines and a by-product of pulp-manufacturing that is generally cheaper than other vegetable oils, its properties make it a suitable raw material for the production of biodiesel and other liquid bio-fuels (Heinze and Liebert 2001, Altiparmak et al. 2007). Biomass also has considerable potential as a feedstock for producing chemicals; this is a particularly attractive prospect because while the economic value of the chemical industry is comparable to that of the fuel industry, the former uses far fewer resources (FitzPatrick et al. 2010). The most significant challenge facing biorefineries in the near future is likely to be a shortage of biomass. Because of its utility as a feedstock for producing oil substitutes, competition for biomass is increasing steadily. Biomass and the productive land area on which it is generated should be used efficiently and in a way that has a low environmental impact throughout the entire production process, from growing through to extraction, conversion and distribution to the end user (Joelsson and Gustavsson 2010). The demand for traditional wood products such as saw timber, boards, pulp and paper is steady and strong, making wooden biomass particularly scarce and valuable. As such, there is a need for new silvicultural regimes that maximize the rate of biomass production and extraction.

In the Nordic countries, the lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) may be a suitable species for producing wooden biomass, fuels and chemicals. Biomass from this species contains a range of important chemicals and nutrients, including high concentrations of lignin, condensed tannins, phenolic species, and compounds such as (+)-catechin and 3,4-dihydoxypropiophenone-3-glucoside (DHPPG) (Stolter et al. 2009). The heartwood of pines normally contains more extractives (such as fatty- and resin acids) than the sapwood (Hillis 1972, Uusitalo 2004).

Lodgepole pine exhibits fast initial growth, which reduces the length of the period when the tree is vulnerable due to its small size. Canadian studies have shown that it performs better than many other species grown in large gaps or clear cuts provided that the spots are not too shady (Coates 2000). Most of Sweden's existing lodgepole pine-stands were planted in the 1970s and 1980s, mainly for pulp production using rather short rotations. Today, lodgepole pines cover almost 600 000 ha of Sweden (Elfving et al. 2001). It has been found that with longer rotations, existing Swedish lodgepole pine stands are also useful for timber production, since their stem volume is approximately 30% greater than that of the dominant pine species in Fennoscandia, the Scots pine (Elfving et al. 2001). Reasons for the superior growth of lodgepole pine under boreal conditions may be an earlier start of growth in spring and a lower required heat sum to start shoot elongation in comparison to Scots pine (Fedorkov 2010).

The properties of lodgepole pine are similar to those of Scots pine, although its density is slightly lower, the fibers are longer, and the proportion of heart wood is greater (Ståhl and Persson 1988, Persson 1993, Andersson et al. 1999). In addition, despite generating more stem biomass than Scots pine in absolute terms, the stem accounts for a smaller proportion of the total biomass in the planted lodgepole pine (Norgren 1996). That is to say, branches and needles account for a greater proportion of the total biomass of the lodgepole pine. Until recently, these fractions have had no commercial applications. However, they and other previously-underused fractions (e.g. bark and cones) are rapidly gaining value as feedstocks for producing fuels and chemicals (Demirbas 2011).

Dense and stable stands of lodgepole pine can be established by direct seeding, which is much less expensive than planting. Furthermore, all of the costs incurred during direct seeding are fixed save for the price of the seed, the process is more readily mechanized than planting, and it facilitates the establishment of stands with the desired density (cf. Wennström et al. 1999). The risk of root and stem deformation is also reduced (Rosvall 1994). Due to these factors and the rapid growth of the lodgepole pine, direct seeding could make it possible to achieve substantial biomass production at a low cost even over relatively short periods of time. However, lodgepole pine silvicultural regimes based on short rotation biomass production have not yet been established and validated. If the objective of the silvicultural regime is to produce feedstocks for bioenergy and biorefineries as well as pulpwood and timber, it will be necessary to quantify the scope for increasing both stem volume and total biomass over time in existing stands created by direct seeding. With a suitable short rotation silvicultural regime, the lodgepole pine could potentially generate large quantities of high quality biomass even under less than optimal growth conditions such as those encountered in the harsh areas of northern Sweden and other northern boreal countries.

The overall objective of this study was to quantify the stem volume and biomass production in lodgepole pine stands created by direct seeding and that were sufficiently old to facilitate the harvesting of a large quantity of biomass for use in biorefineries. A range of different stem densities and growing conditions were considered. To investigate the presence of heartwood (with presumably higher content of extractives) in the young stands, stemwood from sample trees was analyzed. Sample trees were also used to determine biomass of different tree fractions and to make a control of used biomass functions. Furthermore, the direct seeding stands were compared to planted lodgepole pine stands that had been subjected to similar growth conditions.

2 Material and Methods

2.1 Study Sites

The lodgepole pine-dominated stands examined in this work were selected from the Swedish forest company Holmen Skog's forest holdings. Only stands that had been regenerated by direct seeding and were at least 25 years old (which would make them among the oldest direct seeded stands of lodgepole pine in Sweden) were considered. Stands owned by Holmen Skog were examined because they pioneered the direct seeding of lodgepole pine on larger scales in Sweden. Unfortunately, there were no suitable similarly old lodgepole pine stands that had been sown for scientific purposes in Sweden and were available for examination in this work.

Eight stands located in Härjedalen county and another eight in Hälsingland county, giving a total of 16 stands that were divided into four groups using a site index (SI) based on the dominant height of Scots pines at 100 years of age (Hägglund and Lundmark 1977) as estimated by the landowner Holmen skog AB. The thresholds for the different groups were site indices of 16, 20, 22, and 26 m (site index group 1: stand 14-1 to 16-3, site index group 2: stand 20-1 to 20-4, site index group 3: stand 22-1 to 24-1 and site index group 4: stand 26-1 to 26-4; Table 1). The stands' properties are summarized in Table 1. All stands are located at approximately the same latitude (61.8–62.1 °N, WGS84) in the north-central part of Sweden. The stands in Härjedalen, which is close to the Scandinavian mountain range, are situated at greater altitudes and experience harsher weather conditions with a higher annual precipitation of which much falls as snow (Swedish Survey of… 2012), lower temperatures (ibid.), shorter growing season (ibid.), and a lower nutrient availability than do those in Hälsingland, which is located to the east of Härjedalen close to the Gulf of Bothnia. All stands were sown with seeds originating from Canadian trees growing at latitudes of 54.3–55.5 °N, 650–950 meters above sea level and all stands but one had been subjected to pre-commercial thinning (PCT), following the general thinning guidelines for sown lodgepole pine by Holmen skog AB (Normark 2011). First pre-commercial thinning

Table 1. Characteristics of the investigated stands. Site index group 1: 14-1 to 16-3, Site index group 2: 20-1 to 20-4, Site index group 3: 22-1 to 24-1, Site index group 4: 26-1 to 26-4.

Area[a)]	SI and name	Alt. (m.a.s.l.)	Lat. (°N)	M.A.P.[b)] (mm)	G.S.[c)] (days)	T.S.[d)] (°C)	Field layer	Stand age (years)	PCT (age, years)	Thinn. (age, years)
Härj.	14-1	610	61.8	800–900	120–150	800–900	*Call. vulg, Vacc. myrt*	29	20	-
Härj.	16-1	610	61.8	800–900	120–150	800–900	*Vacc. myrt, Emp. nigr*	30	21	-
Härj.	16-2	400	62.1	800–900	120–150	800–900	*Call. vulg, Clad. rang*	30	15+22	-
Härj.	16-3	430	62.1	800–900	120–150	800–900	*Vacc. myrt, Vacc. vit*	29	25	-
Härj.	20-1	420	62.1	800–900	120–150	800–900	*Vacc. myrt*	29	-	-
Härj.	20-2	440	62.1	800–900	120–150	800–900	*Vacc. myrt*	29	20	-
Härj.	20-3	500	62.1	800–900	120–150	800–900	*Call. vulg, Clad. rang*	30	11+20	-
Härj.	20-4	500	62.0	800–900	120–150	800–900	*Vacc. myrt, Ger. sylv*	30	12+21	28
Häls.	22-1	350	62.0	700–800	150–180	900–1100	*Vacc.* sp., *Poac.* sp.	29	14+27	-
Häls.	22-2	320	62.0	700–800	150–180	900–1100	*Vacc.* sp., *Poac.* sp.	30	14+20	30
Häls.	22-3	400	62.0	700–800	150–180	900–1100	*Call. vulg, Clad. rang*	29	18	-
Häls.	24-1	250	61.8	700–800	150–180	900–1100	*Poac.* sp., *Vacc. myrt*	29	13	-
Häls.	26-1	230	62.0	700–800	150–180	900–1100	*Poac.* sp., *Vacc. myrt*	29	8+19	-
Häls.	26-2	290	62.0	700–800	150–180	900–1100	*Vacc.* sp., *Poac.* sp.	30	8+29	30
Häls.	26-3	310	62.0	700–800	150–180	900–1100	*Call. vulg, Vacc. vit*	30	8+23	-
Häls.	26-4	240	62.0	700–800	150–180	900–1100	*Vacc.* sp., *Poac.* sp.	29	8+19	-
Ängom.	-	105	62.4	700–800	150–180	900–1100	*Poaceae* sp.	42	7[e)]	[e)]

a) Härj. = Härjedalen, Häls. = Hälsingland, Ängom = Planted stands at Ängomsåsen used for comparison.
b) Mean annual precipitation.
c) Growing season.
d) Temperature sum.
e) PCT and thinning performed from 6 meters height at each top height increase of 3.5 m.

is performed at 2–3 meters dominant height to avoid excessive clustering after direct seeding. One or more PCTs are then performed to achieve 2300–3000 stems per hectare (spacing 1.8–2.1 m) while first thinning usually is executed at 11–14 meters dominant height, followed by a second thinning before 20 meters dominant height is reached. Stands 20-4, 22-2 and 26-2 had been thinned shortly before being measured (Table 1). The stem volumes removed during thinning were supplied by Holmen Skog and added to the figures for the corresponding stands; 53.0 m^3/ha was thinned from stand 20-4 and 50.4 m^3/ha from stands 22-2 and 26-2.

2.2 Tree Measurements in Circle-Plots

In each stand, eight circular plots with areas of 100 m^2 (radius 5.64 m) were laid out using ArcGIS. Stands 14-1, 16-3, 20-1, 26-2, and 26-3 were shaped in such a way that all eight circle plots could not be accommodated and so only seven, seven, three, six and six plots were defined for these stands, respectively (stand borders were not precisely defined in the register data and so the GIS polygons did not match up perfectly with the stand borders in some cases). The stand where only three circle plots could be measured had a long and narrow shape and was situated next to a road (circle plots could of course not be positioned on the road bank). 117 circle plots were measured in total. The GIS coordinates for the center of each plot were found using two Garmin GPS receivers. Within each plot, all trees with heights $\geq$1.3 m were callipered at breast height, which was defined as 1.3 m (DBH, 1 mm accuracy). A Haglöf Digitech Professional computer caliper was used. About 20% of the trees in each circle plot were randomly selected for measurement of their height and crown length. Tree height was recorded in m (0.1 m accuracy) using a Haglöf Vertex IV digital hypsometer. The nature and abundance of the field layer vegetation in each stand was noted. Field layer vegetation ranged from reindeer lichen (*Cladonia rangiferina*), heather (*Calluna vulgaris*), black crowberry (*Empetrum nigrum),* lingonberry *(Vaccinium* *vitis-idaea)* and bilberry (*Vaccinium myrtillus)* to grasses (*Poaceae* species a.k.a. *Gramineae*) and woodland geranium *(Geranium sylvaticum*) (Table 1). Measurements were performed in autumn 2010 and summer 2011.

2.3 Tree Sampling

Four trees, two from stand 20-2 in Härjedalen and two from stand 26-1 in Hälsingland, were cut for biomass measurements, heartwood analysis and control of biomass functions (see below) in September 2011. The biomass samples were also used for determining chemical content of different tree fractions (Backlund 2012). One small tree with a DBH of 9 cm (9.2 in 20-2 and 9.0 in 26-1) and one large tree with a DBH of 14 cm (13.7 in 20-2 and 14.5 in 26-1) were cut down from each stand. In all cases, the trees were chosen to be representative of the stand in terms of tree dimensions and crown shape, and had sustained no visible damage. The DBH, height and crown length were measured, and the crowns were divided into four strata of equal length according to the biomass measurement schedule proposed by Ahnlund Ulvcrona (2011). A sample branch was collected from each stratum in different directions (a branch in northerly direction from stratum 1, easterly direction from stratum 2, westerly direction from stratum 3 and southerly direction from stratum 4) along with six discs cut from the stem at various heights (base, breast height, 30%, 55%, 70%, 85% of tree height). These and the remaining parts of the trees were weighed in the field to determine their fresh weights. Sample branches and sample discs were then frozen and their dry weights were measured after drying at 85 °C for 48 hours.

An extra two discs were cut from each tree, one from the top of the stem and one from the base, for heartwood analysis. Each disc was dyed with a 50/50 blend of saturated (6 g/500 ml) sulphanilic acid ($C_6H_7NO_3S$) and 10% sodium nitrite ($NaNO_2$) as described by Cummins (1972). This dye gives the heartwood a darker red color than the sapwood, making it possible to determine the amount of heartwood in each disc by measuring the length of the heartwood (mm) along eight radial axes and summing the areas of the eight wedges defined by two adjacent axes and the boundary between the heartwood and the sapwood.

2.4 Comparison with Planted Stands

The measured values were compared to corresponding data for a set of planted lodgepole pine stands at Ängomsåsen (lat. 62.4 °N, alt. 105 m.a.s.l.), 10 km SW of Sundsvall, Sweden. These stands were originally planted by the forestry company SCA in 1970 as part of a spacing trial and were assigned to SLU in 1983 to secure further inventory (Elfving 2006). The studied stands were planted with two-year old, small bare root plants from Toad River, British Columbia (lat 58.45 °N, alt 800 m.a.s.l.). Five different spacings were considered (1.1 m; 1.6 m; 2.0 m; 2.85 m and 4.0 m) and the site has been studied on four different occasions (1983, 1992, 1997 and 2006, i.e. covering a period of almost 40 years (Elfving 2006). A first PCT was performed after seven seasons to remove all naturally generated seedlings. From 6 meters top height, PCT and thinning was executed at each top height increase of 3.5 m to keep the decided targeted stand stem density.The soil at the site is fertile and grass is dominant in the field layer, as is the case for the more productive stands examined in Hälsingland (26-1–26-4). The planted stands at Ängomsåsen are situated 30–50 km from the inventoried and direct seeded stands in Hälsingland.

2.5 Calculations with Respect to Inventory

Height curves were constructed for each circle plot using Näslund's (1936) equation, Eq. 1:

$$H - 1.3 = \frac{x^k}{(a + bx)^k} \tag{1}$$

where H is height (m), x is DBH (cm) and k is a constant that takes a value of 2 for Scots pine; the same value was used for lodgepole pine in this work. The parameters a and b were estimated by linear regression for each circle plot. The volume (on bark) of each tree was then calculated using Eriksson's (1973) equation, Eq. 2:

$$v = 0.1121d^2 + 0.02870d^2h - 0.000061d^2h^2 - 0.09176dh + 0.01249dh^2 \quad (2)$$

where v is the volume (dm^3), h is height (m) and d is DBH (cm). Since Eriksson's equation is not optimal for trees with very small diameters, Andersson's (1954) equation on bark for small pines in northern Sweden was used for all trees with a diameter ≤ 50 mm, Eq. 3:

$$v = 0.22 + 0.08786d^2 + 0.03045d^2h + 0.002809dh^2 \quad (3)$$

where the units are identical to those used in Eriksson's equation (Eq. 2). The volumes were then converted to units of m^3 per hectare.

Elfving (2012a) has developed new biomass functions for lodgepole pine based on data from a sample of 111 Swedish lodgepole pines. One of these new functions (the equation for biomass above stump level) was used to calculate the stands' biomass in this work, Eq. 4:

$$\ln(w) = -2.0949 + 2.2155\ln d - 0.1559\ln h + 0.0524h \quad (4)$$

where w is the dry weight (kg), d is DBH (cm) and h is height (m). The weights were then converted to units of tons per hectare.

Elfving (2012b) has also developed a function to describe the total stem volume production for the planted lodgepole pine stands at Ängomsåsen that were used for comparative purposes in this study. The function expresses the total stem volume as a function of the dominant height and spacing, Eq. 5:

$$\ln(\mathrm{V}) = 0.5546 + 2.8467\ln\mathrm{H} - 1.2014\mathrm{S} + 0.297\mathrm{S}\ln\mathrm{H} - 0.1212\mathrm{H} + 0.005 \quad (5)$$

where V is the total stem volume production (m^3/ha), S is the square spacing at planting (m) and H is the dominant height (m).

2.6 Statistical Analyses

All statistical calculations were performed using MINITAB 15 (Minitab Statistical Software 2007) using ANOVA (Analysis of variance) tables where the hierarchical structure of the data was taken into account.

Studies of data and of residuals did not reveal any heteroscedasticity, distortion, or other type of bias that would require transformation of the data. A significance threshold of 0.05 was used when testing p-values to determine whether the null hypothesis could be rejected.

3 Results

3.1 Stem Dimensions and Stem Volume

There were significant differences between regions and site index groups as well as significant variation between stands for both stem volume and dry weight biomass (Table 2). There were no significant interactions.

Mean DBH, mean height and dominant height varied quite substantially between the site index groups, and between the two regions, ranging from a mean diameter of 8 cm and a mean height of 6 m at the harsher sites in Härjedalen to around 15 cm and 13 m, respectively, at the better sites in Hälsingland (Table 3). There was considerable variation in stem diameters almost regardless of stem density (Fig. 1), with slightly smaller diameters at higher stem densities for all sites except for those in index group 1, where no such trend was observed.

The stem volume of stands ranged on average from around 40 m^3/ha in site index group 1 to about 200 m^3/ha in group 4 and up to almost 300 m^3/ha in the most productive stands in site index group 4 if individual circle-plots are considered (Table 4, Fig. 2). Thinned volumes have been added to stand 20-4 (53.0 m^3/ha thinned out), 22-2 and 26-2 (50.4 m^3/ha thinned out). There was a positive correlation between stem density and stem volume in all four groups, although this was more significant for groups 1 and 4 ($R^2 > 0.3$). The densest plots considered (those with ≥ 3000 stems/ha) were significantly above average in terms of stem wood production and dominant height (Fig. 3). There were significant differences between regions, as well as between SI groups within regions ($p \leq 0.05$) regarding stem volume (Tables 2 and 4).

Table 2. Analysis of variance for stem volume (m^3/ha) and dry weight biomass (tons/ha).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Stem volume						
Region	1	199591	180282	180282	23.47 [b)]	0.000
Site Index group	1	102946	108216	108216	14.09 [b)]	0.003
Region*Site Index [a)]	1	2951	4090	4090	0.53 [b)]	0.479
Stand(Region SI-group)	12	96176	96176	8015	5.70	0.000
Error	101	142079	142079	1407		
Total	116	543743				
S = 37.5062	R-Sq = 73.87%	R-Sq(adj) = 69.99%				
Dry weight biomass						
Region	1	46428.4	39607.3	39607.3	22.31 [b)]	0.000
Site Index group	1	21509.3	22565.6	22565.6	12.71 [b)]	0.004
Region*Site Index [a)]	1	12.7	95.2	95.2	0.05 [b)]	0.821
Stand(Region SI-group)	12	22208.0	22208.0	1850.7	5.29	0.000
Error	101	35338.7	35338.7	349.9		
Total	116	125497.1				
S = 18.7053	R-Sq = 71.84%	R-Sq(adj) = 67.66%				

a) High and low site index group for each region, not exact SI values.
b) Not an exact F-test, because of less than eight circle plots in five of the 16 stands.

Table 3. Stem density, mean diameter, mean height and dominant height for examined stands. Site index group 1: 14-1 to 16-3, Site index group 2: 20-1 to 20-4, Site index group 3: 22-1 to 24-1, Site index group 4: 26-1 to 26-4.

Area	SI and number [a)]	Average number of stems per hectare [b)]	Mean diameter (basal area weighted, cm)	Mean height (basal area weighted, m)	Dominant height (m)
Härjedalen	14-1	1971 ± 647	8.1	6.1	7.3
Härjedalen	16-1	2138 ± 302	8.3	6.1	7.5
Härjedalen	16-2	2900 ± 685	9.6	8.8	10.2
Härjedalen	16-3	2329 ± 150	8.3	7.2	9.0
Härjedalen	20-1	7267 ± 1986	8.8	9.5	11.0
Härjedalen	20-2	3663 ± 460	8.6	7.8	9.2
Härjedalen	20-3	4125 ± 512	9.8	9.8	11.6
Härjedalen	20-4	1863 ± 407	12.8	11.9	13.0
Hälsingland	22-1	1975 ± 692	12.4	11.2	12.5
Hälsingland	22-2	1138 ± 393	13.2	12.0	13.3
Hälsingland	22-3	3325 ± 1609	10.9	9.4	10.9
Hälsingland	24-1	2750 ± 771	13.4	13.0	14.5
Hälsingland	26-1	2338 ± 974	14.6	11.7	13.1
Hälsingland	26-2	1383 ± 838	15.3	13.5	14.7
Hälsingland	26-3	2500 ± 510	12.7	13.1	14.4
Hälsingland	26-4	1675 ± 518	15.7	12.5	13.6

a) H_{100} site index.
b) Standard deviation refers to 1 STD.

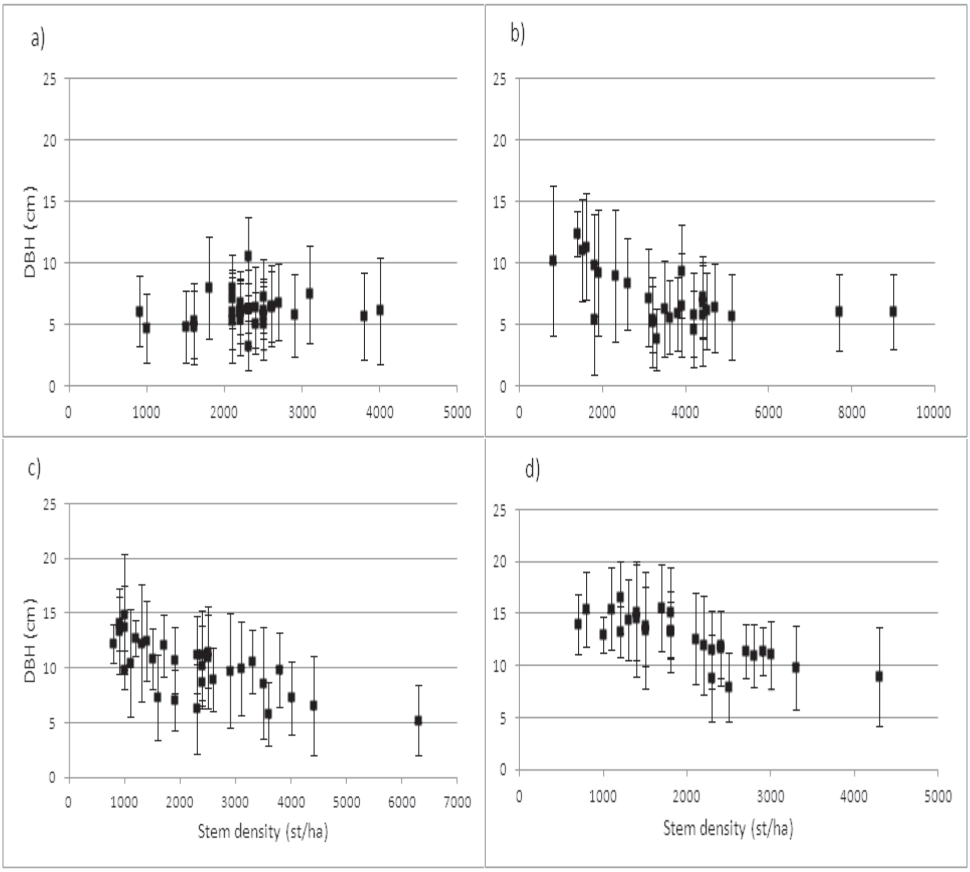

Fig. 1. DBH distribution (average per circle plot with standard deviation as 1 STD, cm) for sown lodgepole pine at different stem densities (stems/ha). a) Site index group 1: 14-1 to 16-3, b) Site index group 2: 20-1 to 20-4, c) Site index group 3: 22-1 to 24-1, d) Site index group 4: 26-1 to 26-4.

Table 4. Mean values for stem volume and dry weight biomass for the four site index groups, with averages for regions, 29–30 years after direct seeding. Differences between regions, and between site index groups within regions, are significant ($p \leq 0.05$).

Parameter	Region	Site index group	Site index	29-30 years after sowing
Stem volume (m^3 ha^{-1})	Härjedalen	1	14–16	38.81
	Härjedalen	2	20	108.56
	Hälsingland	3	22–24	131.33
	Hälsingland	4	26	180.95
	Härjedalen		average	71.30
	Hälsingland		average	154.10
Dry weight biomass (t ha^{-1})	Härjedalen	1	14–16	25.31
	Härjedalen	2	20	51.80
	Hälsingland	3	22–24	64.73
	Hälsingland	4	26	92.55
	Härjedalen		average	37.86
	Hälsingland		average	77.71

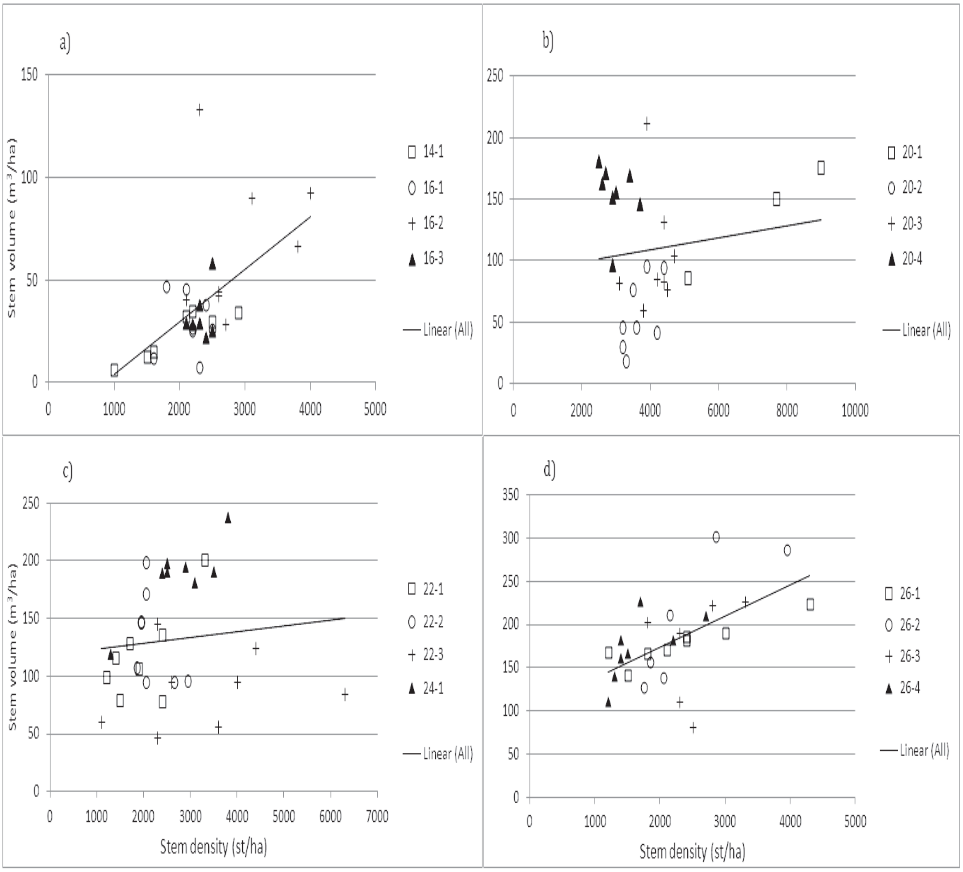

Fig. 2. Stand stem volume (m^3/ha) for sown lodgepole pine at different stem densities (stems/ha). a) Site index group 1: 14-1 to 16-3, b) Site index group 2: 20-1 to 20-4, c) Site index group 3: 22-1 to 24-1, d) Site index group 4: 26-1 to 26-4.

For all of the sampled trees, for which the properties are summarized in Table 5, heartwood accounted for 8.4–25.4% of the total disc area at the stem base (sample tree 2 was the only tree for which heartwood was observed at the top), i.e. all trees had a certain amount of heartwood (Table 5). The larger trees had a greater proportion of heartwood than did the smaller ones.

3.2 Biomass

Dry weight biomass of stands ranged on average from around 25 tons/ha in site index group 1 to almost 100 tons/ha in group 4 and up to about 140 tons/ha in the most productive stands in site index group 4 if individual circle-plots are considered (Table 4, Fig. 4). The results for biomass (Fig. 4) are very similar to those for stem volume (Fig. 2), indicating that the expected positive correlation between biomass production and stem density is present. Around 70% of the total aboveground biomass of the sample was accounted for by the stem, with living branches representing approximately 10% of the total (Fig. 5). The dry weight biomass of the needles was roughly equal to that of the living branches, indicating that the most productive stands examined in this work produced as much as 10–15 tons d.w. of needles per hectare.

Just as for stem volume, there were significant

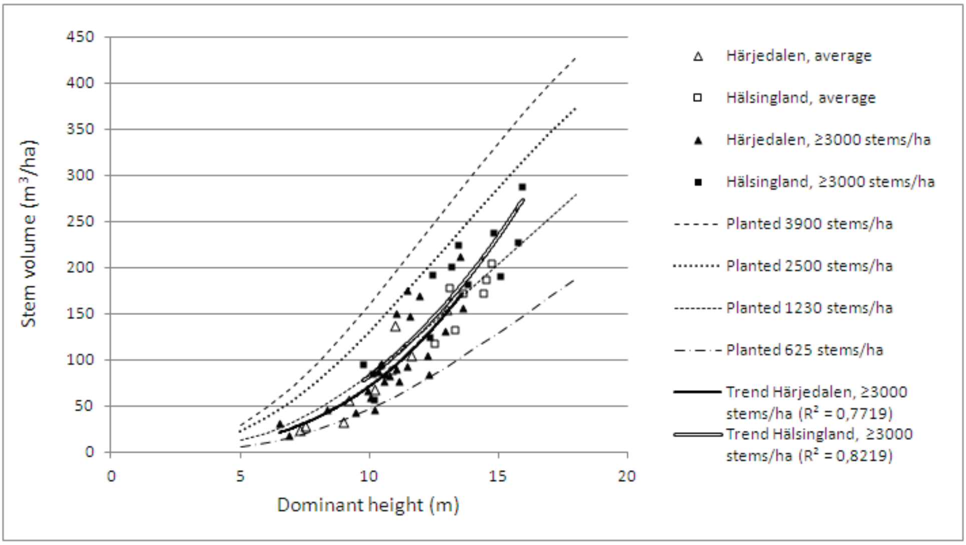

Fig. 3. Stand stem volume (m^3/ha) development with respect to dominant height (m) for operationally direct seeded stands compared with stands planted experimentally in Ängomsåsen (dotted lines) at different stem densities (Elfving 2006, Elfving 2012b). Thinned volumes added to stand 20-4 (53.0 m^3/ha thinned out), 22-2 & 26-2 (50.4 m^3/ha thinned out).

Table 5. Characteristics of sampled lodgepole pines.

Sample tree no	1	2	3	4	Average[a)]
Area	Härj.	Härj.	Häls.	Häls.	-
Stand	20-2	20-2	26-1	26-1	-
DBH (cm)	9.2	13.7	9.0	14.5	11.6 ± 2.9
Height (m)	9.0	12.2	10.8	13.7	11.4 ± 2.0
Crown limit (m above ground)	2.2	2.0	5.1	5.5	3.7 ± 1.9
Green weight (kg)	41.5	118.1	45.3	134.8	84.9 ± 48.5
Dry weight (kg)	15.6	45.7	20.7	57.6	34.9 ± 20.1
Dry matter (%)	37.5	38.7	45.7	42.7	41.2 ± 3.8
Calculated dry weight (kg, Elfving 2012a)	19.1	52.1	19.5	62.8	38.4 ± 22.5
Calculated dry weight of actual dry weight (%)	122.4	114.0	94.2	109.0	109.9 ± 11.8
Heartwood, stem base (%)	8.4	15.3	20.9	25.4	17.5 ± 7.3
Heartwood, stem top (%)	0	2.8	0	0	0.7 ± 1.4

[a)] Standard deviation refers to 1 STD.

differences between regions, as well as between SI groups within regions ($p \leq 0.05$) regarding biomass production (Tables 2 and 4).

3.3 Comparison to Planted Stands

The denser stands examined in this work (≥ 3000 st/ha) yielded results comparable to those for the planted stands (Fig. 3), the most dense of which rapidly attained stem volumes of 350 m^3/ha with a dominant height of 18 meters, in line with Elfving's projections (Elfving 2012b). The results suggest that the stem volume production of the seeded stands may be increasing more rapidly than that of the planted stands at Ängomsåsen and will soon be similar to that of stands planted at a density of 2500 stems/ha.

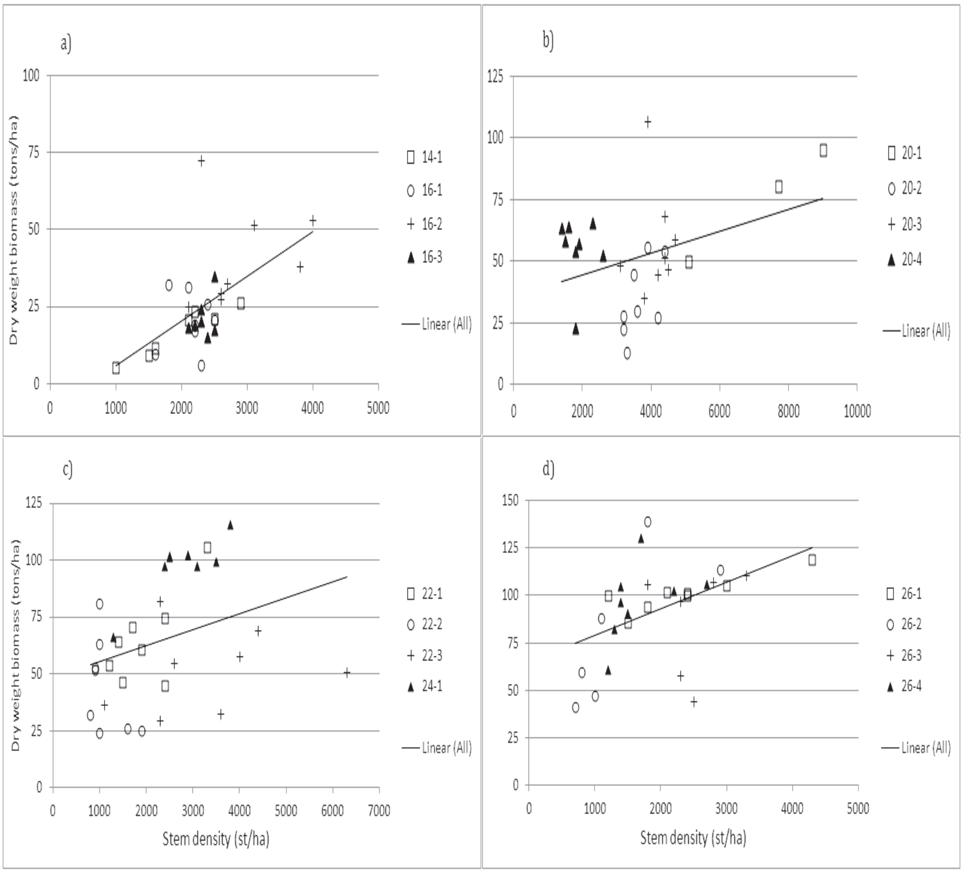

Fig. 4. Dry weight biomass (tons/ha) for sown lodgepole pine at different stem densities (stems/ha). a) Site index group 1: 14-1 to 16-3, b) Site index group 2: 20-1 to 20-4, c) Site index group 3: 22-1 to 24-1, d) Site index group 4: 26-1 to 26-4.

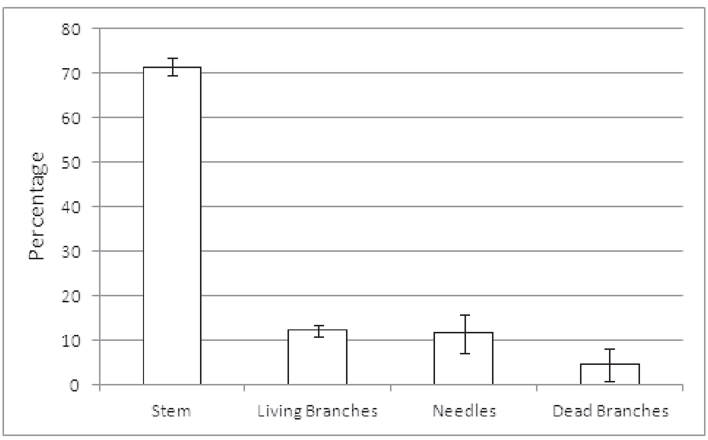

Fig. 5. Partitioning of different tree fractions (weight percent of dry aboveground biomass) for the four sample trees. Vertical bars represent average proportion with standard deviation (1 STD) as staples.

4 Discussion

This study was performed by conducting a survey because there are no experimental direct seeded lodgepole pine stands in Sweden that are old enough to be studied in a controlled experiment. Controlled experiments are generally preferred in forest research, but in cases where it would be impractical or impossible to conduct one, surveys such as that reported herein can provide an indication of the biomass production achievable using current silvicultural techniques. Despite that PCT was performed once or even twice in the studied stands, our results indicate that it may be possible to achieve stem volumes of up to 200 m^3/ha on stand-average with lodgepole pine grown on better sites in mid-northern Sweden and as much as 300 m^3/ha on circle-plot (100 m^2) level within 30 years of direct seeding using current silvicultural methods. This corresponds to up to about 100 tons and 140 tons, respectively, of dry weight biomass per hectare, with 70% of this being stemwood which agrees with results from a partitioning study by Comeau and Kimmins (1989). Needles and living branches account for approximately 10% each according to the small sample of trees analyzed in the study, which matches Pearson et al. (1984) findings of 8.1 and 9.5% fairly well. The amount of dry biomass in the form of needles from our sample trees is particularly substantial – around 10 tons per hectare. The heartwood formation was at least at the stem base significant in all sample trees indicating that the production of extractives in the stem wood should be of importance already at this age, which is of interest when considering selection of material for biorefineries. It should also be considered that the actual annual growth would be high, 15–20 m^3 per hectare in the best sites (cf. Elfving 2006) and in just five years the best sites could have about 100 m^3 more of stem volume.

Almost all stands had been pre-commercially thinned once or twice, which means that the amount of biomass probably should have been slightly higher if that had not been the case. It is unclear how much biomass that has been removed in the stands through PCT, and also how many plants that actually established after sowing. In the more productive groups (SI-group 2–4), a removal of e.g. 1000 plants per hectare through thinning is equivalent to almost 50 m^3 of stemwood at 30 years of age. Thus, it is important to have a clear goal with the silvicultural measures, as PCT and thinning might higher the yield of timber with higher dimensions but lower the biomass yield in a lodgepole pine stand.

This study agrees with previous studies of lodgepole pine (Varmola et al. 2000, Liziniewicz et al. 2012) that higher stem densities generally yield greater quantities of biomass. Liziniewicz et al. (2012) concluded that 2500 seedlings per hectare would be preferable to compromise between growth, timber quality and diameter development. However, this study shows only slight decreases in DBH in even denser stands (up to 4000 stems/ha). Varmola et al. (2000) found that planted lodgepole pine had somewhat higher survival in wider spacings, but basal area and volume production were higher the denser the spacing. Lodgepole pine is known to have wide crowns compared to e.g. Scots pine (Ruotsalainen and Velling 1993). Stand density strongly affects leaf area per tree, but not total leaf area of the stand, and a reduced leaf area efficiency in low density stands can be noticed (Long and Smith 1990), thus denser stands produce stem wood more efficiently.

It is obvious that the stand density of lodgepole pines must be kept below a certain threshold if the main aim is to produce timber of large dimensions. However, when using trees that have been grown for 30 years or less to produce biomass for use in biorefineries, our results indicate that it may be advantageous to establish stands with densities of about 4000 stems per hectare.

There are large differences in productivity between the two geographical regions: all other things being equal, the harsher conditions and higher altitudes at Härjedalen yielded much less stem volume and biomass than did the milder conditions at Hälsingland, indicating that site selection of course is important when deciding where to produce biomass in a relatively short time for biorefineries. More sites have to be evaluated to present general conclusions, but these results give an indication on how much biomass that can be produced in current boreal lodgepole pine forests. Branches and needles are fractions that are becoming more valuable as feedstocks for producing various chemicals, and further research is needed to investigate both the partitioning patterns of lodgepole pine, and the chemical contents of lodgepole pine fractions such as branches, needles, cones and bark.

The denser stands with the highest stand indices in this study could soon be harvested at an age when the harsher sites would need several more years of growth before cutting. This raises an important question: when should lodgepole pine be harvested, and how? Should all of the biomass be harvested at once, or should the large diameter trees be saved for a subsequent timber harvest? One option is to harvest all the trees in a stand once they reach 30–40 years of age, although such early final cutting of pines is not permitted under current Swedish forestry legislation (Skogsvårdslag 1979:429). As such, it may be necessary to change the law to make the cultivation of lodgepole pine in such cases competitive with that of species such as *Salix* for biomass production. Since lodgepole pines are also suitable for products of solid wood, another option would of course be to save some of the stems for timber production. It will be necessary to investigate this option in more detail in order to identify an optimal management regime; in particular, it will be necessary to determine how much biomass can be harvested without sacrificing timber quality or causing damage. Young dense stands have been shown to yield high quality because they have relatively straight stems, thin branches and a favorable wood composition (Ståhl and Persson 1988, Seeling 2001, Watson et al. 2003). Crane corridor thinning might be an interesting option for effective biomass harvesting without harming trees designated for timber production (Karlsson et al. 2012).

The output of Elfving's (2012a) functions was in good agreement with the experimental data for the four sampled trees. It thus seems that the functions work rather well for dense direct seeded lodgepole pine stands: the calculated dry weights are consistent with the actual weights, although the functions tend to overestimate the quantity of biomass produced in direct seeded stands by about 10 percent (Table 5). This might be because denser lodgepole pine stands tend to produce less coarse branches. Despite this drawback, the functions were useful in this study and will be useful in future work since they provide an indication of how much biomass can be obtained from a given direct seeded stand. There are not many biomass functions suitable for dense, direct seeded lodgepole pine stands. Koch (1996) has compiled biomass functions for lodgepole pine throughout the species' natural range in North America, but new functions are needed for lodgepole pine stands of different densities in the Nordic countries because biomass production and partitioning differs between regions and stand stem densities.

The key conclusion of this work is that there is an unutilized potential for cost-effectively growing lodgepole pine in dense stands for biomass production after direct seeding. Considerable amounts of stemwood including heartwood, bark, needles and branches (extractives included) could be obtained within about 30 years and, thanks to presumably high actual annual growth, within another five to ten years much higher amounts could be expected. It may be possible to develop regimes for short(er) rotation forestry that could produce substantial amounts of inexpensive biomass for biorefineries in only a few decades.

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