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Mikołaj Lula
Supervisors: Mateusz Liziniewicz
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Mikołaj Lula

Supervisors: Mateusz Liziniewicz, Southern Forest Research Centre,
Swedish University of Agricultural Sciences
Harald Säll, Department of Forestry and Wood Technology,
Linnæus University

Examiner: Per Magnus Ekö, Southern Forest Research Centre,
Swedish University of Agricultural Sciences

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Master thesis in Forest Management, EUROFORESTER- Master Program SM001
Advanced Level (A2E), SLU course code EX0630, 30 ECTS

Abstract

The objective of this study was to assess quality of lodgepole pine (*Pinus contorta* Dougl. var. *latifolia*) sawn boards derived from stands established in four different initial densities i.e. 1.1 m x 1.1m, 2.0 m x 2.0 m, 2.85 m x 2.85 m, 4.0 m x 4.0 m. The logs were extracted from unthinned plots that were 44-years-old growing in northern Sweden,. The quality was assessed in respect to knots properties as knot size, knots number, position on the board, living status of the knot ect. It was found that wood quality regarding mean knot size and knot are ratio (KAR) was decreasing with growing space availability. There were no differences between spacings in terms of knot frequency. There was also no evidence of differences in knot type variation between the treatments. Thus, conventional spacing of 2.0 m x 2.0 m (2500 seedlings ha^{-1}) seems to be a reasonable compromise between timber quality, economics and growth. However, there is a potential to decrease planting densities without depreciation of knots parameters.

Keywords: timber quality, Lodgepole pine, initial spacing, knot properties, Pinus contorta, planting density

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Introduction

The distribution and lodgepole pine characteristic

Lodgepole pine (*Pinus contorta*) is a two needle pine species, native for western North America (Wheeler and Critchfield, 1985). It is distributed over a large areas from Baja California (31°N) up to the central part of the Yukon Territory (64°15’N), that makes it one of the most widespread coniferous species on the American continent (Critchfield and Little, 1966). Within its natural range lodgepole pine grows under a wide spectrum of climatic and edaphic conditions. However, a majority of stands are associated with relatively dry and nutrients poor sites (Wheeler and Critchfield, 1985). Lodgepole pine is also more resilient with respect to altitudes than any other pine species (0-3900 m.a.s.l). It is found in both high, subalpine mountains regions and in the plain areas along the Pacific coastline (Critchfield and Little, 1966). Due to high adaptability and habitat tolerance lodgepole pine has developed different morphological and genetic forms. It varies from low, shrubby woodlands through relatively small but thick trees in the forests of Cascade Mountains up to high stands of high merchantable value in the interior sites. Due to its geographical variations taxonomists have distinguished four subspecies of lodgepole pine: *P.contorta var.contorta* (shore pine), *P.contorta var.bolanderi* (bolander pine), *P.contorta var. murrayana* (Sierra lodgepole pine) and *P.contorta var. latifolia* (Rocky mountain lodgpole pine) (Critchfield, 1980).

The inland race, *Pinus contorta Dougl. var. latifolia* is a tall, thin barked tree that usually does not gain large diameter (Wheeler and Critchfield, 1985). It can reach the heigh up to 30-40 m in the age of 100-150 years, (Hagner, 1983). Lodgepole pine is a highly pioneer species and its regeneration relates on fire. Its serotinus cones can remain close even up to 40 years, until high temperatures during fires allowed them to release seeds. After seeds release, it can form very dense (100 000-2500 000 seedlings per ha), pure stands (Lotan et al., 1985; Backlund, 2013). Nevertheless, it can be also found in mixtures with other coniferous e.g. Picea plauca Voss, Abies lasiocarpa L.

Owning to its morphological features and wood properties, it is the most valuable variety of lodgepole pine from economical perspective. In some parts of Canada e.g. in British Columbia, it is one of the most important commercial tree species (Elfving et al., 2001). It has a significant role in the lumber and pulpwood industry. However, big amounts of wood that have been attacked by mountain pine beetle (*Dendroctonus ponderosae*) are used as a fuel wood (Scott, 2007). Between the years 1990-2012 over 18 million hectares of forest in British Columbia were touched by massive beetle epidemic. Total lose by the year 2017 when invasion is believed to stop, was estimated to reach 752 million cubic meter of lodgepole pine wood (Safranyik et al., 2010). As a consequence pulp and paper industry is going to be significantly affected by great supplies of bad quality wood and wood with blue stain (*Grosmannia clavigera*) sapwood incursion.

Lodgepole pine in Sweden – background

The first lodgepole pine test plantations in Sweden have been established already in the 1928. However, used provenances (south of 55°N) has been not successful (Karlman, 1981). Up to the year 1960 planted area of lodgepole pine was rather limited. Nevertheless, existing trials indicated its better growth and similar wood properties comparing with native Scots pine (*Pinus sylvestris L.*) (Elfving et al., 2001).

First results from the yield experiments indicated production superiority of lodgepole pine over Scots pine (Hagner, 1971). The effect was increasing with decreasing site fertility (Hagner, 1971). This fact led to increasing interest in production oriented cultivation in northern Sweden (Elfving et al., 2001). Moreover the shortage of raw materials for the pulp industry was foreseen at the end of twentieth century. In order to counteract expected deficit introduction of fast growing exotic tree species was suggested as a solution and lodgepole pine was used as an alternative (Liziniewicz et al., 2012; Hagner, 1983).

Since 1965 the lodgepole pine planting area was gradually increasing until the year 1980. To cope with future demand for planting material 140 ha of seed orchards have been established until 1987 (Elfving et al., 2001). These were estimated to ensure a reforestation of more than 50 000 ha of lodgepole pine stands per year (Elfving et al., 2001). Nevertheless, lodgepole pine afforestation has been restricted to 14 000 ha annually by the National Board of Forestry and the 60° latitude was the southern border down to which planting was allowed (Skogsstyrelsen.se, 1993) . Currently, stands dominated with lodgepole pine covers approximately 660000 ha (Skogsstyrelsen.se, 2014). Sweden is a third country after Canada and United States in terms of lodgepole pine productive area (Hagner, 1983).

Introduction of lodgepole pine have been accompanied byprovenance studies. Full scale trial plots have been established all over the country (Elfving et al., 2001). The evidence suggested that planting material collected from interior sites of British Columbia and Yukon Territory performed best (Karlman, 1981: Elfving et al., 2001 ; Hagner and Fahlroth, 1974) . Contrary to Scots pine, northward transfer of lodgepole pine was more favorable (Elfving et al., 2001). It was concluded that climate in lower altitudes in British Columbia is similar to conditions in northern Sweden. Thus transmission range should not be greater than 2-5° to the north (Hagner and Fahlroth, 1974).

Growth and stability

Comparing with native Scots pine, the volume production superiority has been estimated to be up to 36% greater on the same sites (Elfving et al., 2001).The potential explanations of higher growth rate are earlier development of shoots and needless, faster leaf area growth during the year, earlier crown closure, higher needle longevity, greater leaf area index (Leverenz and Hinckley, 1990; Elfving et al., 2001). Due to these factors, lodgepole pine might be able to absorb more solar radiation than Scots Pine during the growing season (Elfving et al., 2001). Moreover lodgepole pine needles are characterized by lower share of nitrogen (Ingestad and Kähr, 1985;Stolter et al., 2009). That is why its leaf area index can be significantly higher than in case of Scots Pine with the same nitrogen content (Alriksson and Eriksson, 1998). It might be the reason of higher above ground biomass production on the sites where nitrogen is a limiting factor. Lodgepole pine has more efficient resource acquisition than Scots pine. The majority of the biomass is allocated in roots and needles instead of wood (Elfving et al., 2001).

Lodgepole pine exhibits also lower mortality after planting and during establishing phase than Scots pine (Ackzell, 1993). This differences can be explained by better resistance for biotic and aboitic stresses and relatively good frost hardiness. However its vulnerability for moos browsing compare to Scots Pine is unclear (Ball and Dahlgren, 2002). Niemela and Danell (1988) found that total biomass consumption was greater for Scots pine on fertile sites but lodgepole pine was more browsed on poorer sites. The same studies indicated that bark removal was grater in logepole pine compare to

Scots pine (Niemela and Danell, 1988). Lodgepole pine in Sweden can suffer from moose and field vole (*Microtus agrestis*) (Hansson, 1985). It is also more resistant for early frost in the autumn. Lodgpole pine is not a host for as many fungi and insects as native Scots pine. Nevertheless it can be affected by snow blight (*Phacidium infestans*) and Scleroderris canker (*Gremmeniela Abietina*) (Elfving et al., 2001).

Older stands can also suffer from wind and snow damages. Risk of windthrows is enhance by stand height and artificial regeneration. Susceptibility to wind is attributed to relatively elastic stem and branches. It is affecting how snow and wind loads transmit on the tree (Elfving et al., 2001). Selection of proper site, suitable planting method and use of early, less intense thinnings seems to be crucial in the risk reduction. Moreover lodgepole pine have lower compare to Scots pine ability of natural pruning (Elfving et al., 2001).

Timber quality

Lodgepole properties as pulp and paper production

Lodgepole pine utility for pulping can be compared with native Scots Pine properties. Due to longer and slander fibers lodgepole pine pulp shows higher breaking length and bursting strength (Sable et al., 2012). However Scots pine is more resistance for tearing (Elfving et al., 2001). Both species can be pulped together.

Lodgepole pine has a lower, even up to 10%, bark content compared to Scots pine and Norway spruce (*Picea abies* (L.) Karst.). However the percentage of knot wood in relation to total stem volume content was estimated to be higher in lodgepole pine wood (1.0-1.7%) than in other coniferous (0.7%). Basic density is similar for both species. Nevertheless lodgepole pine is likely to exhibit slightly lower values (Andersson, 1987).

Lodgepole pine as sawn timber

Lodgepole pine timber is suitable for construction materials. However its general strength characteristic is lower compare to Scots pine (Andersson, 1987). It has slighter bending strength and modulus of elasticity (MOE). Lodgepole pine has considerably higher proportion of heartwood (Ståhl and Persson, 1988;Del Rey Morris, 2011). Its maximum can reach from 10 up to 30% of relative tree height and it is decreasing towards the tree top (Andersson, 1987b). Stem form over and under bark in logepole pine is considered to be better compared to Scots pine (Persson, 1993). Nevertheless stem shape quality is decreasing with increasing diameter (Andersson, 1987b).

Relationship between stand density and wood quality is a crucial issue in timber production from production and economical point of view. Growth, yield and quality of individual trees is considerably affected by choice of initial stand density. In general, timber quality is increasing with the increase of initial density (Pfister, 2009). There is a positive correlation between tree diameter and thickest branch diameter at breast hight (Briggs et al., 2007; Pfister, 2009). Wide spacing enhanced branch retention on the stem base, while in denser stands natural pruning occurs earlier in the rotation and has a higher rate (Persson, 1972). The rate of live crown recession affects wood properties such as size and number of knots. Moreover it changes wood characteristic: fiber length, wood density and the proportion of sapwood and juvenile wood (Gartner, 2005). Those features have direct impact on utility of the row materials for mechanical wood processing, pulp and paper production (Ballard and Long, 1988).

Number and thickness of branches in the log is a main criteria of wood quality assessment for specific end-products. Mean and maximum knots size are commonly considered in quality grading and product value (Green et al., 1999). Grading studies on the lodgepole pine timber showed that substantial amount of sawn-wood is downgraded due to knots size (Fitzimons, 1989). Increasing individual knot diameter have negative correlation with wood stiffness, longitudinal tensile strength, compression strength parallel to the grain and bending strength (Desch and Dinwoodie, 1996). Most of the failures are associated with deviate angle of cells and distorted grain in knot surrounding where wood compression occurs (Hart, 2010). In mechanical processing it is a cause of wood splits occurrence. Moreover, module of rupture (MOR) and module of elasticity (MOE) are negatively affected by increasing knot size (Grant et al., 1984). As was found in the study of Gupta (2004) and Benjamin et al. (2009), number of knots regardless to their sizes reduces wood strength for both compression and tension. Large and frequent knots are unwanted also in pulp-industry (Macdonald and Hubert, 2002).

The study goal

At the early stage of the large scale, lodgepole pine introduction in Sweden the main concern was given to its pulping properties (Hagner, 1983; Ulvcrona et al., 2013; Backlund, 2013). However, the foreseen shortage of raw material for pulp industry has not occurred. Thus, great amounts of harvestable wood will stay for longer time in the stands and be accessible for sawmill in the following years (Backlund, 2013).

Extensive experiments showed that lodgepole pine can be used as a high quality sawn timber that is comparable with Scots pine (Elfving et al., 2001). Thus there is a need to carry out researches on wood quality of lodgepole pine in respect to different silvicultural treatments. Initial spacing together with appropriate thinning regimes and artificial pruning can be important part of short rotation sawn wood production (Liziniewicz, 2014; Hart, 2010; Elfving et al., 2001). Many similarities between lodgepole pine and native Scots pine gives evidence that they could be managed in the same way during whole rotation (Elfving et al., 2001). In the current study, the quality of lodgepole pine sawn wood derived from four different spacings was analyzed. For the purpose of the study, the quality was described by knots properties of the boards. The study was conducted in only in unthinned stands growing in northern part of Sweden close to the town of Matfors. The main hypothesis was that size of knots in lodgepole pine sawn boards is increasing with increasing spacing.

Materials and methods

Study area and experimental design

The trial has been established and planted in 1970 close to village of Matfors (62° 21'N, 17°20'E) located in northern Sweden. The experimental area was divided into 4 blocks and 20 sample plots (Figure 1). There were 5 plots within each block. The size of the plot was around 0.088 ha and was of a square shape.

Planting material was two-year old, bare root seedlings of the Toad River provenance form British Columbia district in Canada. Lodgepole pine have been planted in five initial spacings i.e. 1.1 m x 1.1 m – 8300 seedlings ha^{-1}, 1.6 m x 1.6 m – 3900 seedlings ha^{-1}, 2.0 m x 2.0 m -2500 seedlings ha^{-1}, 2.85 m x 2.85 m – 1200 seedlings ha^{-1}, 4.0 m x 4.0 m 600 seedlings ha^{-1}. Each spacing was replicated once in the block and spacing was randomly assigned to the plot within the block. In this study spacings 1.10 m x 1.10 m and 2.0 m x 2.0 m was considered and referred later as "dense" spacings. Planting densities of 2.85 m x 2.85 m and 4.0 m x 4.0 m were referred later as "wide" spacings.

Survival rate in the first year after planting was 86%. Thus, in 1971 three additional plots were established as a potential replacement for the plots with high mortality (plots 21 – 23, Figure 1). In the year 1976, the average survival was 80% with mean height of 136 cm. Five years after planting whole area have been pre-commercial thinned in order to remove naturally regenerated broadleaves and coniferous.

In the brief inventory in the spring of 1983, mean height was estimated about 4 m. Small variations in height between different plots have been noticed. In the plots with the densest spacing (1.1 m x 1.1 m) snow damages occurred. Some of the trees have been bended.

The highest mortality of 56% has been observed in plots planted in the widest initial spacing of 4.0 x 4.0 m.

All the plots within experiment were inventoried in years 1983, 1992, 1997 and 2006. All trees were permanently numbered prior to the first inventory. At the time of each inventory, diameter at breast height measured for all trees. At the same time existing quality defects were registered i.e. spike knots, double tops etc. Height and crown height was measured for randomly selected sample trees within each plot according to the procedure for the permanent sample plots (SLU). Unfortunately, the stand was completely damaged by wind in winter 2014 in age of 44 years old (Table 1).

Table 1. Stand data from 2014. Diameter on the breast height (DBH), top height (H), site index (SI) in four different initial spacings.

Initial Spacing (m)	DBH (cm)	H (m)	SI (m)
1.10x1.10	12.35	17.40	26
2.00x2.00	16.00	17.60	25
2.85x2.85	20.60	17.50	25
4.00x4.00	24.20	16.55	23.5

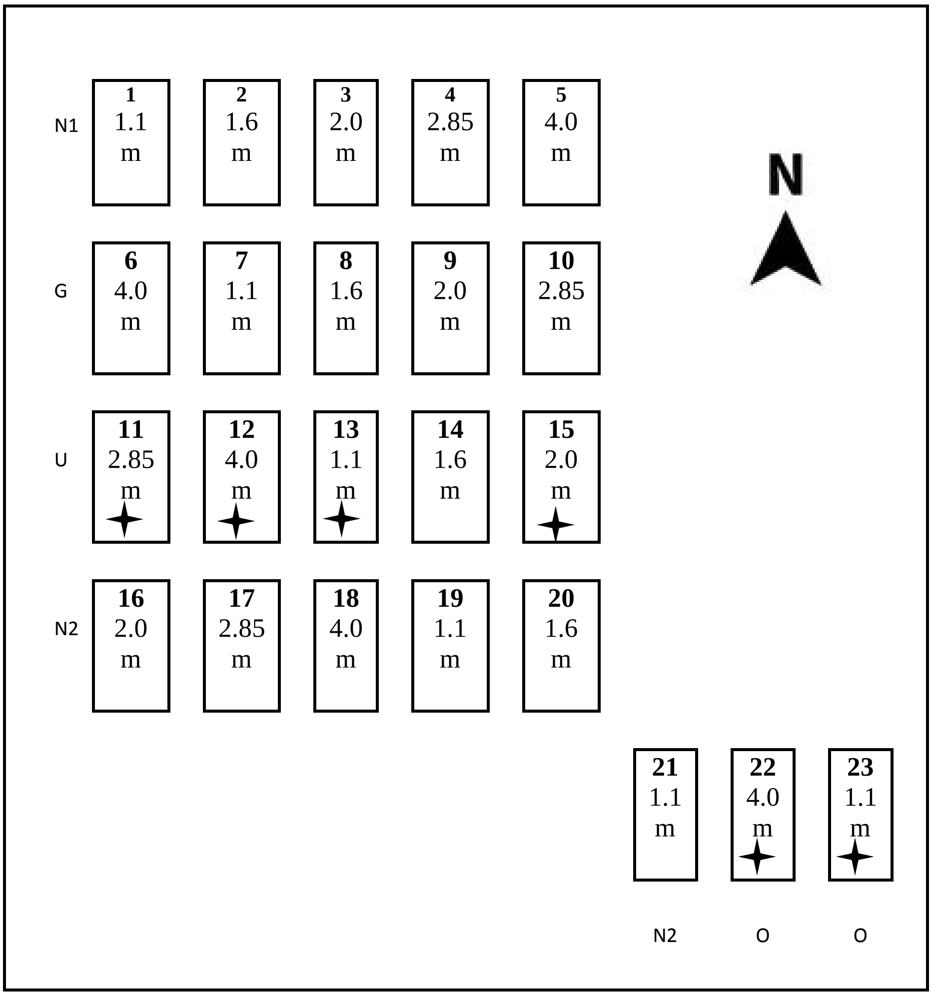

Figure 1. The design of the experiment 1207 in Ångomsösen. The bold numbers indicate plot . N1, N2, G and U indicate the applied thinning regime and in the range from 1 to 20 indicate blocks. The plots 21 – 23 are additional plots established 1 year later. Black star indicates plots that have been used in the study.

Two thinnings regimes (N, G) have been applied in the experiment (Figure 1) and there was also a control treatment where the thinning was not done (U). The intensity of thinning was regulated by removed stems or removed basal area in N and G, respectively. In the N, thinning has been done considering the current top height i.e. mean height of 100 thickest trees/ha^{-1}. However, block N2 have been reduced up to 625 stumps per hectare with the top high of 16.5 m (table 2). In 1.1 m x 1.1 m spacing plot, number of trees per hectare during each treatment have been reduced to the next, higher grade (table 2). In the G thinings have been done according to the table.2. Action have been taken when basal area before (BAb) was greater than basal area after thinning (BAa), (table 3) of more than 10%. The N has been applied in two blocks while G in one block.

Table 2. Thining intensity according to stem number per hectare used in the N thinning.

Spacing	1.1 x 1.1m	1.6 x1.6 m	2.0 x 2.0 m	2.85 x 2.85	4.0 x 4.0
Stem nr / ha	8300	3900	2500	1230	635
Top high at first thinning (m)	6	9,5	13	16,5	-

Table 3. Thinning intensity according to basal area (m2/ha) used in the G thinning

Top high (m)	9	10	11	12	13	14	15	16	17	18+
Basal area after thinning (m2/ha)	17,0	20,2	22,6	24,5	26,0	27,2	28,2	29,0	29,5	30,0

Only unthinned plots (U) were included in the study. It was due to limited financial sources and complicated extraction of timber in damage stands. Unthinned stands were not so severely damaged as thinned i.e. most trees were standing. Moreover, wind damages could have an effect on quality properties and sawing process.

Study of timber quality

Material sampling

To assess an impact of spacing on quality properties of sawn wood, 92 logs have been randomly selected from six unthinned plots in the spring 2014 (Figure 1). All logs were about 4 m long. Only bottom-logs were extracted. It was due to limited financial sources. Moreover, there were still some years to final felling. Lodgepole pine boards have been cut out by means of circular saw according to the pattern shown in Figure 2.

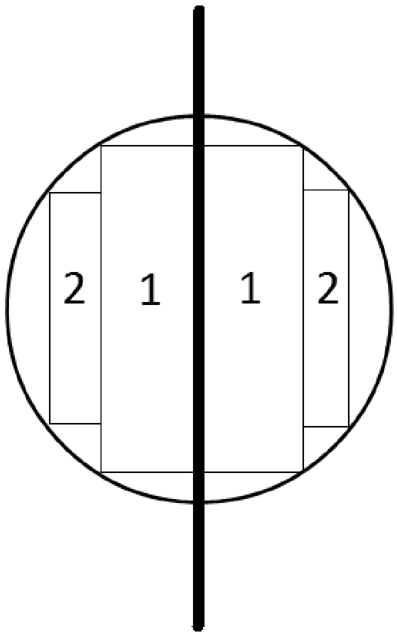

Figure 2. Sawing pattern. The circle indicates the steam cross section. Rectangles indicates boards. The numbers inside each rectangle indicates board position. In this study boards with position 1 were called central boards; boards in position 2 were called outer boards. In the study 95% logs allowed to extract two boards indicated as “1”. Only central boards were analyzed in the study.

The logs were sawn into boards from the central and outer part of the steam in order to achieve maximum production. Boards size varied from 95 mm x 50 mm up to 145 mm x 50 mm. Due to the just few outer boards from 2.0 m x 2.0 m and 1.0 m x 1.0 m only inner board were analyzed in the study.

Knots measurements

Data regarding knots properties was collected in the spring 2016. Measurements have been done separately on each of four boards surfaces. Two greatest diameters have been measured for each knot parallel to board edges. The position of each knot has been recorded as a distance from the lower part and from left edge of the board. Knots were classified in order to their position on the board surface i.e. face knots (FK), edge knots (EK), splay knots (SK), arris knot (AK) and margin knots (MK) according to the classification shown on Figure 3 (hackney.ac.uk, 2010).

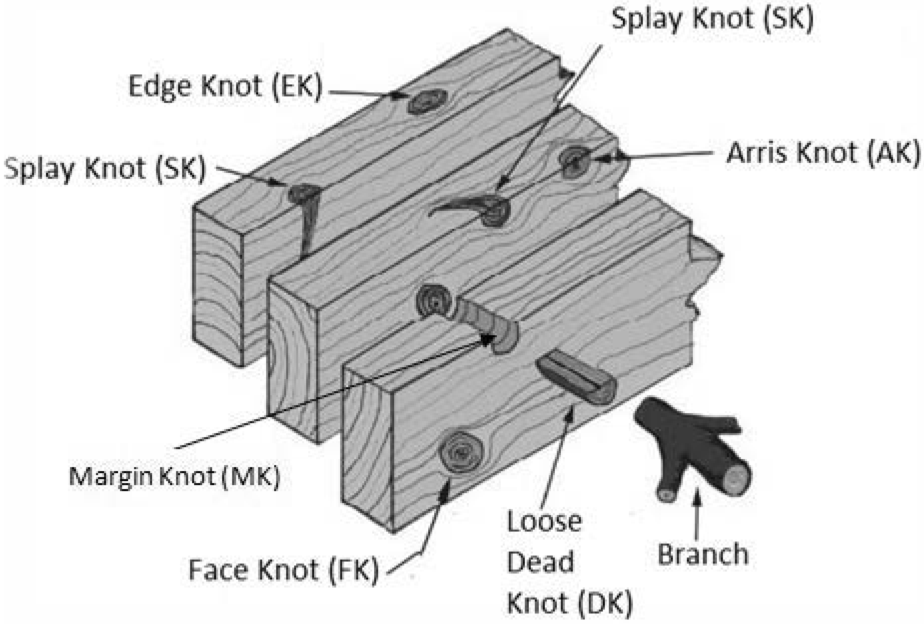

Figure 3. Knots types regarding to sawing pattern (hackney.ac.uk, 2010).

Differentiation for live (LK) and dead knots (DK) was done. Knot was define as live when at least ¾ of its wood were ingrown with the surrounding wood (Pfister, 2009).

Analysis

There were no replication of 2.0 m x 2.0 m and 2.85 m x 2.85 m and just two replicates of two other spacings. Thus, the statistical comparison between treatments was not done. A detailed description and presentation of the collected data was done. The mean size of the knot was an average of two diameters (D, d). Knot area (S) was calculated from the equation:

$$S = \pi \cdot 0{,}5a \cdot 0{,}5b \text{ where,}$$

S – ellipse area; a – diameter (D); b - diameter (d)

.

Knot are ratio (KAR) was sum of all knots areas in relation to total board area. KAR was calculated separately for both live and dead knots. In order to predict pruning effect only inner board surface i.e. surface closest to the pith, was taken into consideration. The summary of total volume production was done for the unthinned plots selected for extraction of the logs.

Microsoft Office Excel was used for the quantitative analysis and visualization.

Quality assessment

Visual assessment of sawn boards quality was done according to grading system from *Blå boken* (Jarbring, 2010). Knots were classified into three grades i.e. A, B, C depending on board dimension and surface. Maximal size of live knot was restricted in each class. Class A was showing the best quality while in B and C quality was decreasing respectively.

Results

Knot size, frequency and distribution

The lowest number of knots has been found in the densest spacing (1.10 m x 1.10 m) and was on average around 29 knots per board. The greatest amount of knots i.e. 39 knots occurred in the boards coming from trees planted in the widest spacing (4.0 m x 4.0 m) (Table 3). Number of knots was increasing with increase of initial spacing (Figure 4).

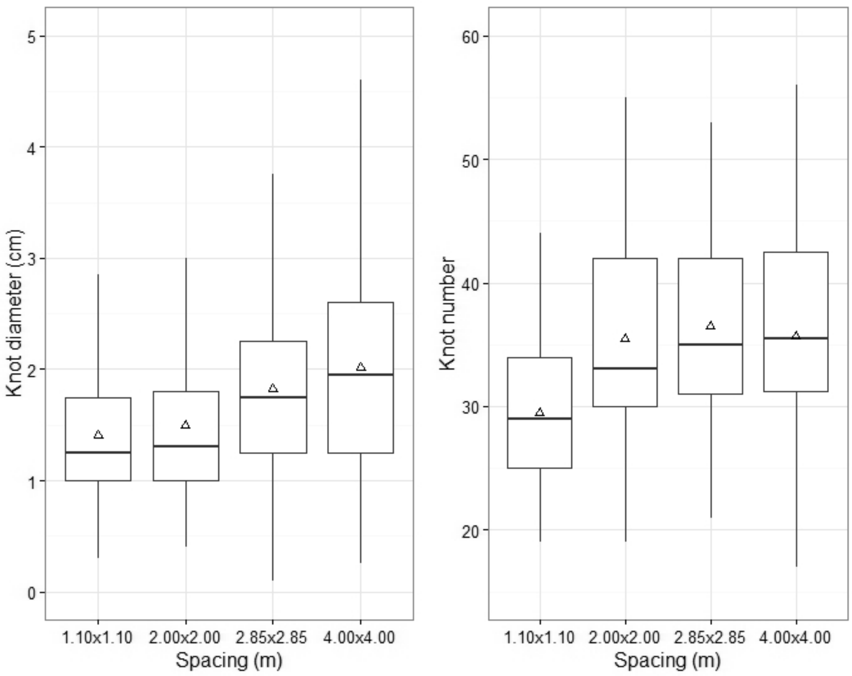

Figure 4. Diameter of knots (cm) and number of knots per board in four different spacings. Box shows the middle 50% of values. Horizontal line inside each box is the median. The upper and lower whiskers shows the highest and the lowest value respectively. White triangles indicates mean value.

The smallest mean knot diameter has been found in the lowest initial density and was 1.41 cm. The greatest mean knot diameter was found in the 4.0 m x 4.0 m and was 2.4 cm (Table 4).

Table 4. Knots properties in four different spacings.

Spacing	Mean knot diameter (cm)	Max. knot diameter (cm)	Nr.knots/board	Dead knots (%)	Live knots (%)
1.10x1.10	1,41	4,75	29	35,9	64,1
2.00x2.00	1,50	4,7	35	29,7	70,3
2.85x2.85	1,86	18	36	17	83
4.00x4.00	2,06	15,7	39	10,1	89,9

The greatest number of knots was around one meter height from the root in all spacings. Above one meter height there was slight decrease in knot number in all treatments (Figure 5). Diameters of knots in all treatments increased towards the top of the board. Knot with the biggest mean diameter i.e.

2.44 cm was found in the 4.0 m x 4.0 m spacing in the 375 cm height- class (Figure 6). The smallest knots were found in two densest spacings and had an average diameter of about ~ 1.10 cm.

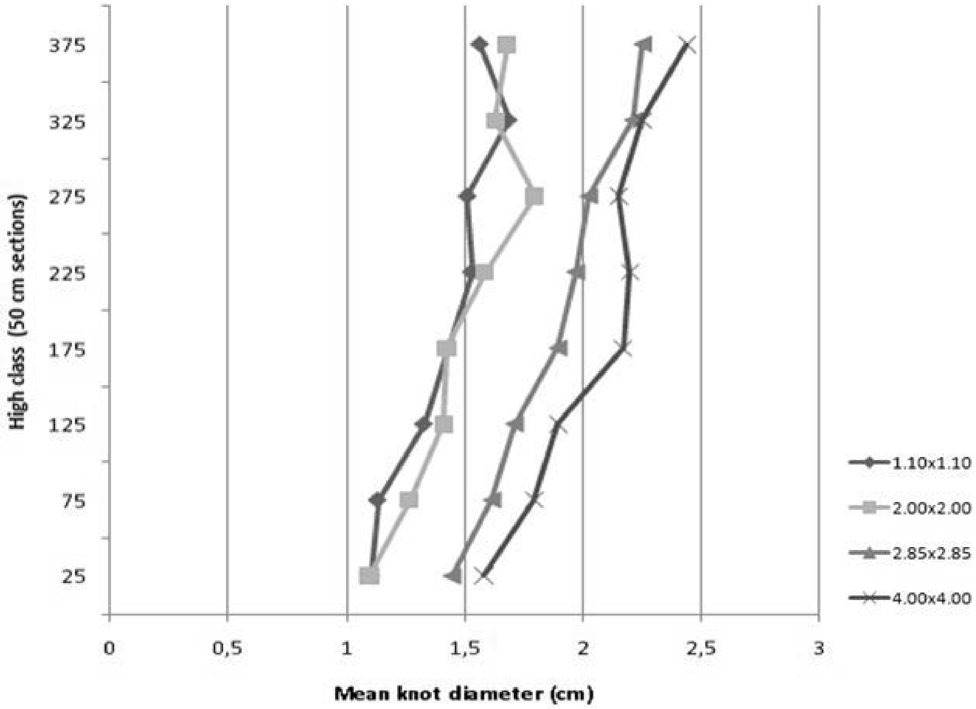

Figure 5. Average number of knots per board in 50 cm high classes in different spacings.

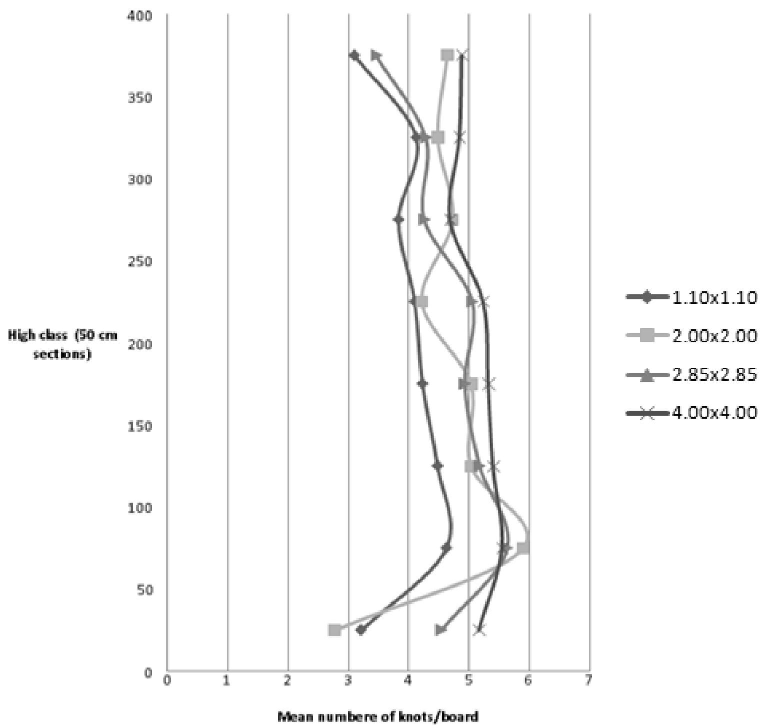

Figure 6. Average knot diameter in 50 cm height classes in different spacings.

Knot size was increasing with increasing log root diameter regardless of spacing (Figure 7). Correlation for denser spacings was higher (R = 0.2 – 0.22) than for wider 2.85m x 2.85m and 4.0 m x 4.0 m spacing i.e. 0.07 and 0.10, respectively.

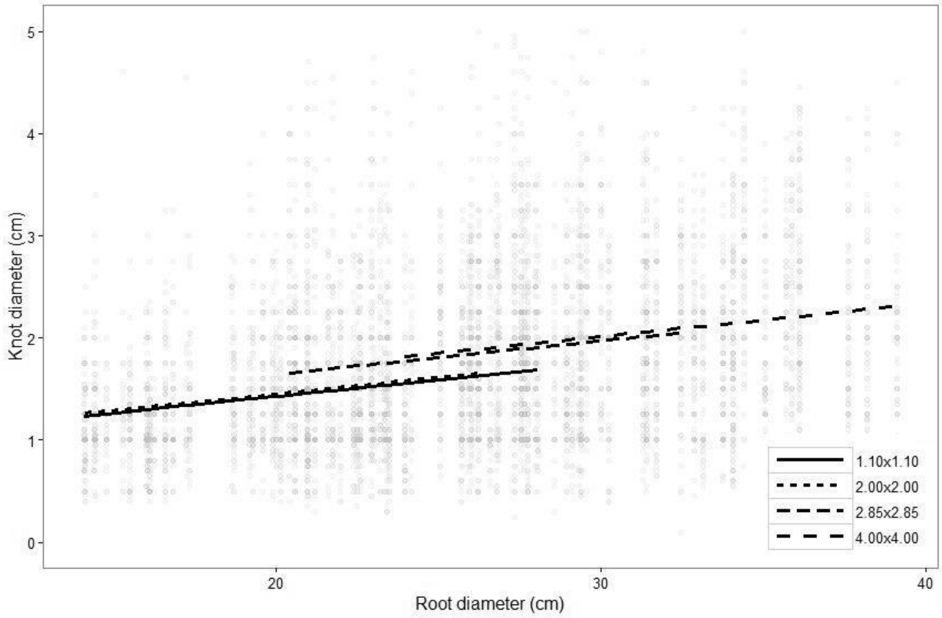

Figure 7. Mean knot diameter in relation to the root diameter of the log in four different spacings.

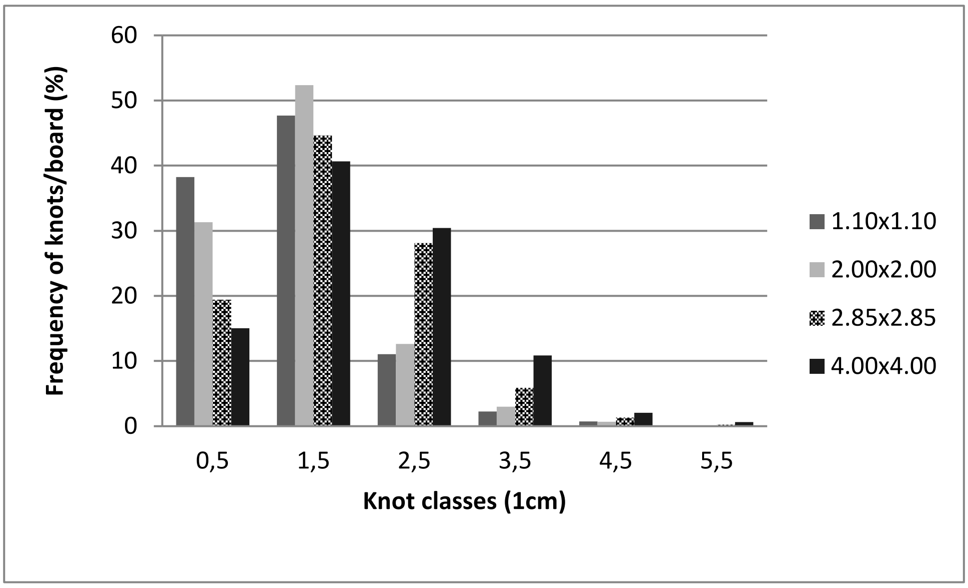

Figure 8. Frequency of knots per board in 1cm diameter classes in four different initial spacings

The greatest number of knots was found in class between 1 and 2 cm (Figure 8). The knots with diameters greater than 3.0 cm were rare. Knots that ocuured in the number lower than 0.2 % were not shown on the Figure 8. Greatest share of small knots i.e < 1.0 cm was present in the densest spacing 1.1 m x 1.1 m. Number of small knots was decreasing with increase of initial spacing. Frequency of konts with diameter grater than 2 cm was increasing with decrising spacing density.

Knot soundness

The relative number of dead knots was the highest in the densest spacing 1.1 m x 1.1 m (Figure 9). The frequency of dead knots was decreasing with increasing spacing density. The highest share of live knots was found in the widest spacing 4.0 x 4.0m i.e. 90 % (Figure 9).

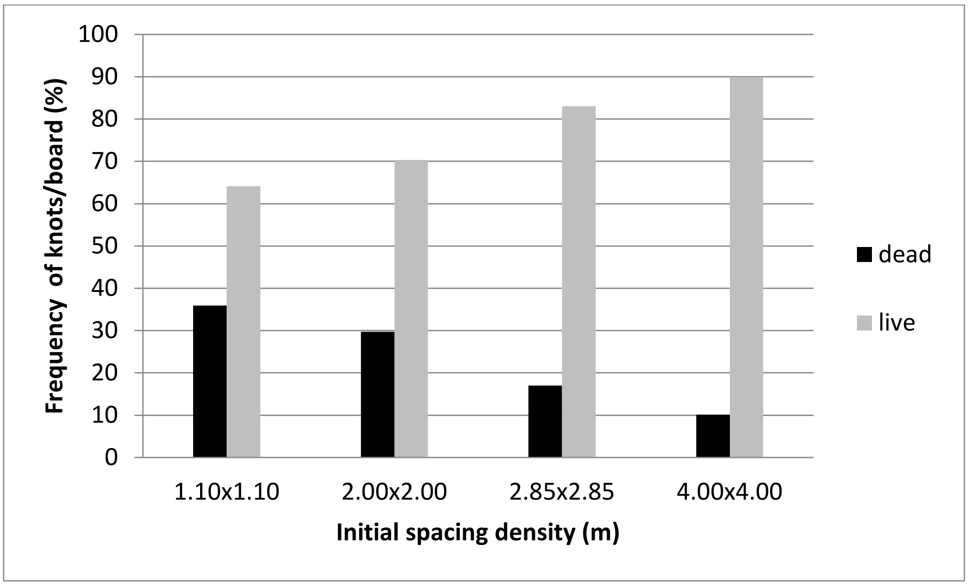

Figure 9. Frequency of dead and live knots in four different initials spacings.

Knot area ratio

Knot area ratio (KAR) of both dead and live knots was increasing with increasing distances between planted seedlings (Figure 10). KAR was slightly higher in 1.10 x 1.10 m spacing for dead knots than for a live ones. The difference between KAR of dead and live knots were greater in spacings wider that 2.0 x 2.0 m. The absolute difference between KAR of dead and live knots were 0.35 % and 0.32 % in 2.85 x 2.85 m and 4.0 x 4.0 m spacings, respectively.

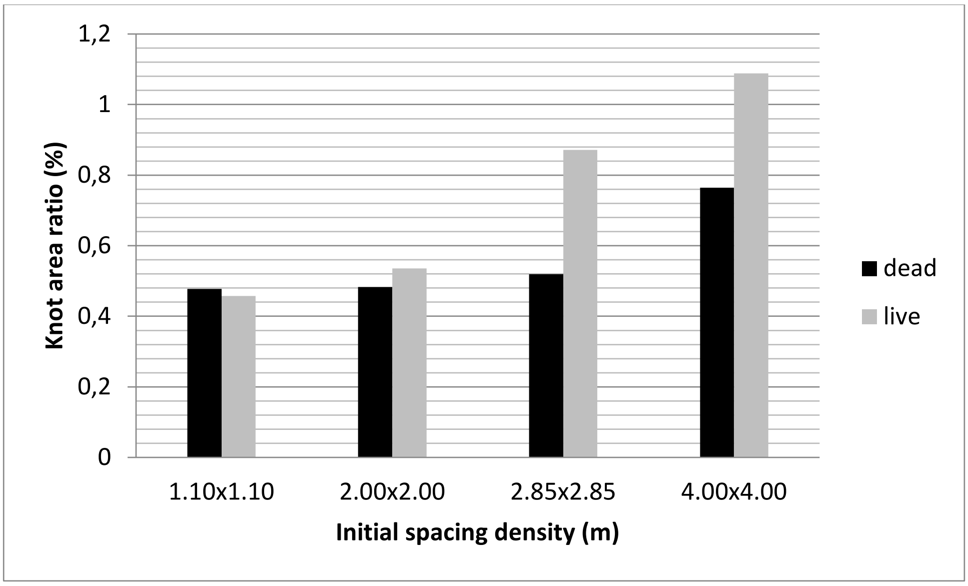

Figure 10. Live and dead knot area ratio (KAR) in different initial spacings.

Knot types

The most frequent type of knot was face knots (FK) (Figure 11). The number of FK was increasing with decreasing planting density. In the 4.0 x 4.0 m spacing there were about 22 FK knots per board. Arris (AK) and splay knots (SK) were less common. Margin knots (MK) were found only few times during the measurements thus, they were not considered in the Figure 11.

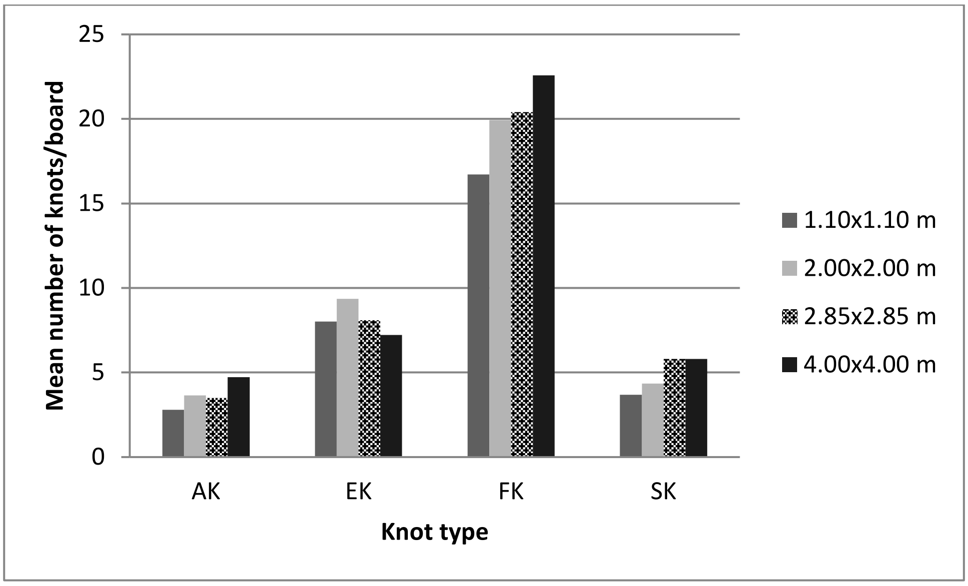

Figure 11. Mean number of different knot types per board in different spacings. AK is arris knot, EK is edge knot, FK is a face knot, SK is a splay knot (for knot type definition check Materials and Methods).

Knot size on different board surface

Knots thickness regardless board side was increasing with decreasing initial planting density (Figure 12). The biggest knots occurred on the board surface closest to the pith regardless of spacing. Size of the mean knots on the outer surface was lower by 0.16 – 0.46 cm. In 4.0 m x 4.0 m spacing knot sizes on both surfaces were similar.

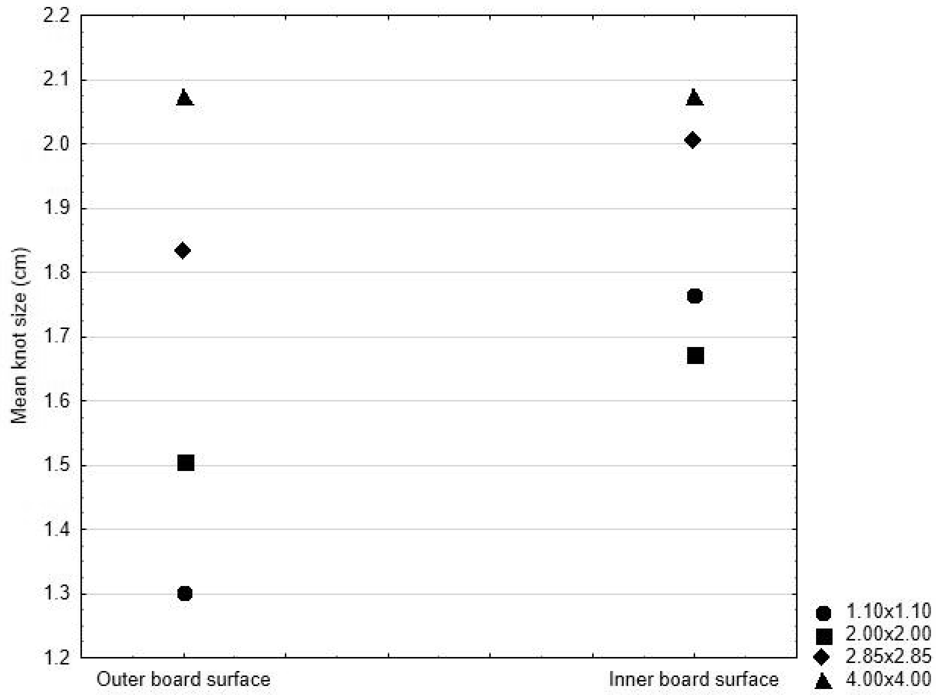

Figure 12. Mean knot size on inner and outer board surface in four different spacings.

Overall quality

Number of knots in A grade was decreasing with increasing spacing. Frequency of knots from A class was higher than 50% in 1.1 m x 1.1 m and 2.0 m x 2.0 m spacing. In wider spacings knots in B grade were dominant.

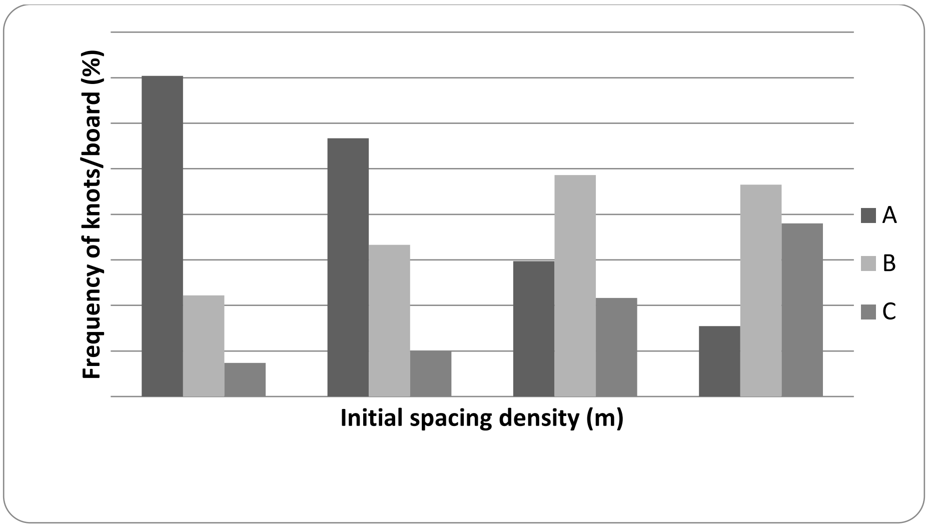

Figure 13. Knots frequency of different quality grade classes in four different spacings.

Discussion

Quality parameters

Knot size, frequency and distribution

In this study knot size was affected by initial planting density. An average knot diameter was increasing with decreasing spacing density. The same relationship between initial planting density and branch diameter has been found in the study on lodgepole pine in southern Sweden conducted by Liziniewicz et al. (2012). Liziniewicz et al. (2012) found that the mean branch diameter increased significantly with increasing spacing. Ballard and Long (1988) and Moberg (1999) found that in lodgepole and Scots pine stands respectively, branches in the wider planting density were thicker than in higher densities. It was due to longer retention of living branches on the trunk in wider spacing. Consequently, the knots in the sawn-wood had bigger sizes.

Mean knot diameter in all treatments increased with increasing height from the stump. Stöd and Kilpeläinen (2006) found that diameter of sound knot of Scots pine calculated in a constant distance from the pith in merchantable part of the steam was increasing with the tree high.

In the current study mean knot diameter increased with increasing root diameter of the log regardless of spacing. Thinner trees had relatively smaller knots compare to thicker trees. However, the correlation coefficients were low i.e. between 0.07 and 0.22. Ikonen et al. (2009) concluded that increase of spacing is enhancing diameter growth of single trees increment study. Trees growing in denser spacings were thinner in root diameters compare to trees growing in denser spacings. Liziniewicz et al. (2012) found that trees in smaller diameter classes were more frequent in denser spacings while share of big diameters trees was higher in wider planting densities. Diameter growth of the tree was found to be positively correlated with branch size growth (Vestøl et al., 1999; Johansson, 1992). Thus, it indirectly affects knots sizes. Studies of Johansson (1992) and Briggs et al. (2007) showed that there were no effect on branch number in different spacings. In the current study, there were 20% more knots within the 4.0 m x 4.0 m spacing than in the 1.1 m x 1.1 m spacing. However, boards coming from the 1.1 m x 1.1 m spacing had smaller dimensions i.e. 82% of total board area from 4.0 x 4.0 m spacing. That was probably the reason of lower for approximately 20% total knot number per board. Thus, knot number should not be influenced by planting density and it can be concluded out of the results of this study.

A large proportion of knots on the boards from spacing denser than 1500 trees ha^{-1} were relatively small i.e < 1.5 cm. On the boards from wider spacings i.e. < 1500 trees ha^{-1}, there were more knots with diameter greater than 2.5 cm. Results showed that knots in denser initial density i.e. > 1500 trees ha-1 were not only smaller but also more uniform in terms of size compare with wider spacings. Knots in wider spacings i.e. 2.85m x 2.85 m and 4.0 m x 4.0 m were bigger and varied more in size. Greatest amounts of the large diameter knots in the wide spacings can be explained by the fact that branches stays alive for a longer time (Ballard and Long, 1988).

Knot soundness

Living knots were larger in diameter than dead knots. This observations were in line with the study by Stöd and Kilpeläinen (2006) that in 77% of sample Scots pine trees had the live knot larger than dead knot. There were also more living knots than dead knots in the studied material regardless of initial spacing. As long as the branch remains alive there is continuous growth of limb junction and the bole fibbers. After the branch has died, bole fibbers become disconnected with the limb. In the timber it results in live (intergrown) and dead (encased) knots respectively (Kretschamann, 2010). Thus, the frequency of dead knots can be associated with the number of dead branches in the living tree. In this study increasing frequency of dead (encased) knots with increasing planting densities have been observed. Lower competition in wider spacings was the reason of longer retention of living branches on the stem.

Dead knots tend to be loosen in the timber. However, wood fibers around both encased knots and remaining wholes are less distorted than in case of live knots (Luca, 2011). Thus cross grains are more problematic in intergrown knots (Kretschamann, 2010). The grading systems for Scots pine sawlogs in Sweden includes knots soundness as a quality parameter. It restricts size of sound knot (live) to 12 cm in II, III and IV grade (SDC.se, 2014).

Knots area ratio

In the current study it was found that KAR regardless to the knot type was increasing with increasing spacing. There are not many studies regarding the effect of initial planting density on KAR in coniferous stands. Grant et al. (1984) found that KAR reduces modulus of elasticity (MOE). However, KAR is not precise quality indicator since it does not include dimensions and individual location of each knot (Oh et al., 2010). Studies of Mäkinen (1999) showed limitations in reduction of knottiness by controlling stand density. Pfister, (2009) found that heavy thinning i.e. removal of ~ 40% of basal area (BA) did not dramatically increase KAR in Norway spruce plantations, compare to light thinned stands i.e. removal of ~16% of BA. Liziniewicz (2014) did not found differences in KAR, between thinned and unthinned stands of Scots pine.

Knot types

Different types of knots appear as a result of log sawing pattern (Lowell et al., 2014). Shape of each knot depends of the angle of the saw cut with respect to the axes of the branch (Williams et al., 2003). Regardless to the type all knots reduces strength and stiffness of sawn products (hackney.ac.uk, 2010). However, knot located closer to the edges of the plank reduces the strength more than those situated centrally (hackney.ac.uk, 2010).

Classification of knots applied in this study (Figure 3) is not commonly used. Thus, it did not allow relating results of this study to any other observations. Moreover, knot types classifications in relation to the board edge is rather rare.

Nevertheless, some grading systems e.g. National Grading Rules for softwood dimension lumber in United States of America, are taking into consideration knots location regarding to the board edge. Sizes of knots located on the wide face of the board are restricted. Knots size can be increased proportionately from the size permitted at the edge to the size permitted at the centerline of the plank. Knots that are overlapping more than ½ the narrow board face are considered as edge knots (wclib.org, 2008).

Knot size on the different board surfaces

The differences between the mean knot diameter on the inner and outer surfaces of the board ranged between. 0.16 - 0.46 cm regardless of spacing. It seems that there is a small decrease in the mean knot diameter with increasing distance from the pith in wider spacings than in denser spacing. Similar studies about lodgepole pine are rare. Studies from another species indicated that the mean diameters of the knots increases with increasing distance from the pith (Stöd and Kilpeläinen, 2006; Gjerdrum and Høibø, 2008). Stöd and Kilpeläinen (2006) found that the largest diameter of individual knot in Scots pine sawn boards increased from the pith outwards. Gjerdrum and Høibø (2008) found that irrespectively to the type, knot size gradually increased with the distance from the pith.

Overall quality

The best overall boards quality was found in the densest spacing of 1.1 m x 1.1 m. Spacing of 2.0 m x 2.0 m showed relatively good quality compare to wider spacings. There was a great difference between 2.0 m x 2.0 m and 2.85 m x 2.85 m spacing. Ledin (2010) in his study from northern Sweden found that quality parameters as thickest branch diameter, relative branch diameter and butt log taper differed significantly between 1.6 x 1.6 m and 2.0 m x 2.0 m compare to 2.85 m x 2.85 and 4.0 x 4.0 m spacings. The worst general quality of lodgepole pine stems have been found in 4.0 m x 4.0 m spacing (Ledin, 2010).

Management implications

Initial spacing beside thinnings, can be a silviculture tool to control growth, mortality and natural pruning of branches (Gort et al., 2010). It can indirectly improve wood quality in terms of knots properties (Ballard and Long, 1988). The grates achievements can be done especially in lower, most valuable part of the steam (Stöd and Kilpeläinen, 2006). This studies shown the opportunities of wood quality improvement in lodgepole pine with respect to knots by application of suitable spacing.

Initial spacing of 2.0 m x 2.0 m (2500 seedlings/ha) has been commonly applied for lodgepole pine in northern Sweden (Liziniewicz et al., 2012; Martinsson, 1983). The conventional spacing i.e 2.0 m x 2.0 m showed good results in production of acceptable quality timber from lodgepole pine (Liziniewicz, 2014). Current study supports these findings. Wood quality in terms of knots properties in 2.0 m x 2.0 m spacing had appropriate properties that will be accepted by the industry. There was significant decrease in quality between boards from 2.0 m x 2.0 m spacing and 2.85 m x 2.85 m spacing. This indicates that there is a possibility for the increase of initial spacing. Moreover, wood quality obtained in 2.85 m x 2.85 m might be considered as on option if artificial pruning will be applied. Mäkinen (1999) concluded that use of artificial pruning can optimize high quality timber production. Fitzimons (1989) found that artificial pruning can improve lodgepole pine quality, significantly even up to first class joinery timber.

Acknowledgment

My full appreciation and sincerest thanks goes to my main supervisor Mateusz Liziniewicz for his patience, support, and scientific guidance during the whole Master Thesis research.

I would like to also take the opportunity to thank my co-supervisor Prof. Harald Säll for his invaluable technical assistance.

This study was financed by BO RYDIN Found and IKEA(EUROFORESTER scholarship).

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Appendix: Knot types (data collection, spring 2016)


Photo 1. Face knot

Photo 2. Edge knot


Photo 3. Splay knot


Photo 4. Margin knot


Photo 5. Live knot


Photo 5. Dead knot