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Growth Rate and Wood Properties of Norway Spruce Cutting Clones on Different Sites

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The effect of growth rate on weight density and strength properties of three Norway spruce cutting clones growing on three different sites in different geographic locations was studied. The purpose was to follow variation in wood physical and mechanical properties and in quality between fast-growing clones grown in environments differing in nutritional and soil properties and climate within the boreal zone. The cloned trees had been selected on grounds of good growth, health and quality. The cuttings were collected from three-year-old seedlings and rooted. The rooted cuttings were planted in the 1970's and they were on average 26 years old at a time of felling. The variation of weight density was studied within the annual ring and within the stem between the juvenile and mature wood from the pith to the bark with an X-ray densitometric method. The average annual ring width (and latewood proportion, %) varied between the clones from 2.92 ± 1.36 mm (15.34%) to 3.30 ± 1.25 mm (11.80%) and between the sites from 2.76 ± 1.07 mm (14.71%) to 3.70 ± 1.22 mm (13.29%). The mean weight density was 0.461 ± 0.077 g cm^{-3} and latewood density 0.750 ± 0.125 g cm^{-3} in this material. The mean modulus of elasticity was 9.88 ± 1.43 GPa, modulus of rupture 67.51 ± 11.50 MPa and weight density of the test samples (ρ_{12}) 414 ± 44 kg m^{-3} in mature wood. The parameters studied showed clearly that the environment had a large effect while the three clones differed from each other similarly in the different sites, e.g. the fastest growing clone was fastest on all sites.

Keywords density, growth rate, mechanical strength, modulus of elasticity, modulus of rupture, Norway spruce
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1 Introduction

Norway spruce (*Picea abies* (L.) Karst.) is economically and ecologically one of the most important tree species in Scandinavian countries. In sawmilling, pulping and papermaking the improvement of end-product quality and economical yield is the result of modern precision of machinery; therefore, modifying and unifying wood and fibre properties by breeding and silvicultural practices would allow a further gain (Corson 2002, Wimmer et al. 2002).

Many genetic improvement programs have concentrated on growth and yield and outer wood quality, such as stem form and the size and number of branches. However, wood properties such as wood density, strength and chemical composition of wood are very important for wood processing. Genetic parameters of wood density have been published for a wide range of species. The results across species show high heritability, low genotype by environment interaction and strong positive age-age correlations i.e. selection based on early measurements is efficient (e.g. Rozenberg and Cahalan 1997, Hannrup 1999).

Wood density is a commonly used wood quality indicator that is related to other wood properties, such as timber strength and shrinkage, as well as pulp yield and properties (e.g. Panshin and de Zeeuw 1980, Harris 1993). Wood density is mainly influenced by genotype, ageing of the cambium, and growth rate (e.g. Olesen 1977, Blouin et al. 1994, Zhang 1995, Zhang and Morgenstern 1995, Lindström 1996, Hylen 1997, Zhang 1998, Saranpää 2003). In conifers, increased growth rate usually leads to a greater increase in earlywood (low density) than in latewood (high density) formation and also delays the transition from juvenile wood to mature wood (e.g. Larson 1969, Zhang et al. 1996, Koga et al. 2002, Saranpää 2003).

This study examined the variation in wood properties of three Norway spruce clones that were planted on three sites of different fertility and geographic location within the boreal zone. This gave us the opportunity to find out the extent of variation in wood properties between trees of the same genotype and how much variation the environment causes between the trees of the same clone. The wood properties studied included growth increment, latewood proportion, earlywood and latewood density and strength properties (MOE, MOR). The samples were further analysed for their lignin content and lignin modification (Raiskila et al. 2006a, 2006b) and decay resistance (Ritschkoff et al. 2006).

2 Materials and Methods

2.1 Background of the Cutting Clones A, B and C

Parent trees (*Picea abies* (L.) Karst.) of the cutting clones A, B and C were chosen for rejuvenation by visual assessment in the 1960's using good growth, health, quality (e.g. stem straightness and branching) and vigour as selection criteria. The mother tree of clone A was selected from a natural forest in Loppi (24°30´E, 60°44´N, 120 m above sea level) in southern Finland, Europe. The thinly-branched pointed crown was 24.5 m in height and 5.5 m × 6.0 m in breadth. Brush-type branches were at an angle of 90° to the main stem. The diameter of the straight and supporting trunk with bark was 45.9 cm measured at breast height (BH) and the height of the tree was 35.0 m.

The mother tree of clone B was selected from the natural forest in Jokioinen (23°29´E, 60°48´N, 100 m above sea level) in southern Finland. The age of the tree was between 80–100 years and it was growing on a moraine soil type. The tree was considered to have a good stem form and the crown was dark green in colour. The length of the densely branched normal-type tree top was 25 m and its diameter was 4 m × 4 m. The branch-type was normal and the branch angle of tree was 20°. The straight and full trunk was 45 cm in diameter (BH) and 33 m in height.

The mother tree of clone C was selected from the natural forest in Loppi (24°30´E, 60°44´N, 120 m above sea level). The thin-branched linear top of the tree was 28.0 m long and 6.5 m × 6.5 m wide. The branch angle was 90–110°. The tree showed vigorous shoot growth in length. The straight trunk was slowly tapering. The trunk diameter was 58.2 cm (BH) and height 36.5 m.

After open pollination the seeds were collected from the three mother trees and germinated for

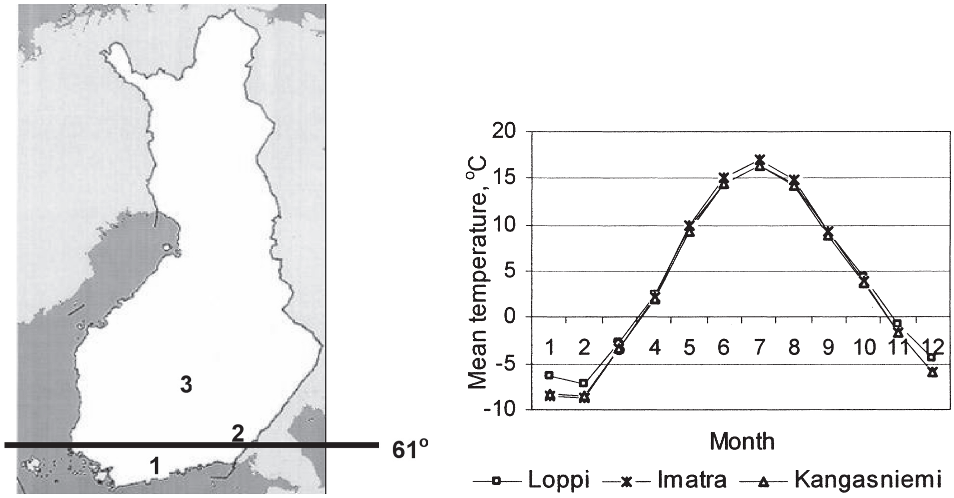

Fig. 1. Monthly temperature variation (temperature sum) during the years 1970–1999 in Loppi (1, □), Imatra (2, ⚹) and Kangasniemi (3, △) in Finland.

rejuvenation. When the seedlings were three years old, the cuttings were collected and rooted. The best trees were then selected on the basis of good growth and vigour and planted on the three different growing sites (Loppi, Imatra and Kangasniemi) in Finland (Fig. 1).

2.2 Materials

Disks and logs of wood were sawn at breast height (about 1.3 m) from the stems of 44 trees (5 stems/clone/site, except that only 4 stems were sampled from clone C from Kangasniemi) representing the three different Norway spruce (*Picea abies* (L.) Karst.) cutting clones (A, B and C) growing at three different sites: Loppi (24°26´E, 60°37´N, 120 m above sea level), Imatra (28°48´E, 61°08´N, 55 m above sea level) and Kangasniemi (26°41´E, 61°57´N, 103 m above sea level) in Finland. The trees were planted in 1975, 1974 and 1979 and they were 26 (Loppi), 28 (Imatra) and 24 (Kangasniemi) years old at the time of logging in winter in 2001–2003. The growth sites Loppi (site 1) and Imatra (site 2) were nutrient rich old agricultural lands (soil type loam). Kangasniemi (site 3) was medium fertile moraine soil type and *Myrtillus*-type forest (Cajander 1926). Mean temperature during the years 1970–1999 is presented as a monthly average on the three sites in Fig. 1. At site 2 the mean temperature was about 1 °C higher than on the two other sites during the growth period (June, July and August) and at site 1 the mean temperature was about 1 °C higher in late autumn, winter and early spring (October–March) over the 30 years. On site 1 the trees had been planted in lines and on sites 2 and 3 they had been planted into a square pattern (2 × 10 m and 2 × 8 m, respectively). The distance between the trees was 2 × 2.5 m (site 2) and 2 × 2 m (site 3). Kangasniemi showed higher mortality among cuttings than Loppi and Imatra. However, due to the wide planting distance the gaps did not have any effect on growth of individual stems. Loppi and Imatra were nearer canopy closure than Kangasniemi due to the higher growth rate. No silvicultural practices had been applied for the stands before and the stands were approaching first thinning stage. Trees situated at the edges of the forest were not selected. Trees with visible defects were omitted.

Samples were taken avoiding knots and compression wood. Wood logs (0.5 m long) were sawn for strength measurements and wood discs (10 cm thick) were taken for annual ring width and weight density measurements and for chemical analyses. The samples (about 5 g) for lignin analysis were taken from the growth rings 3–6 in the heartwood and from the growth rings between 13 and 22 in the sapwood.

2.3 Annual Ring Width and Weight Density Measurement

Annual ring width and weight density were measured at breast height (1.3 m) from all the 44 trees representing the three clones (A, B and C) from the three sites (1, 2 and 3). Wedge-like pieces were sawn from the wood disks in the direction of radius and then air-dried for 6 months. For the measurement strips 5 mm in thickness were cut from the dried wood pieces from the pith to the outer surface. The moisture content of the samples was stabilized at 20 °C at a relative humidity (RH) of 65% for 3 weeks. The samples were placed on a film and exposed to X-rays (16 kV, 20 mA) from a distance of 2.5 m for 5 min (Saikku 1975, Mäkinen et al. 2002b, Jaakkola et al. 2005). The films were scanned with an image resolution of 25.4 µm pixel^{-1} (256 grey levels). Density analysis was performed using WinDENDRO™ software version 6.4 (Regent Instruments Inc., Canada). Density values were obtained by comparing the measured grey levels to a standard of known physical and optical density. For each annual ring the mean values for ring density, earlywood density and latewood density (weight density, 12% moisture content, g cm^{-3}), as well as the latewood percentage, were determined. In addition, the total widths of annual ring, earlywood and latewood were determined. A transition point (TP) between earlywood and latewood was separately defined for each ring as follows:

$$TP_r = MAX_r - [(MAX_r - MIN_r) \times 0.3)] \quad (1)$$

where MAX_r and MIN_r are the maximum and minimum densities of annual ring *r*. The factor 0.3 was found to have the best fit in the data (Jaakkola et al. 2005).

2.4 Modulus of Elasticity and Modulus of Rupture

Modulus of elasticity (MOE) and modulus of rupture (MOR) of wood were measured in samples taken at breast height from all the 44 stems representing the three different clones from the three different sites. Boards (20 mm × 20 mm × 341 mm) were sawn from mature wood of the wood logs. The moisture content of the samples was stabilized at 20 °C at relative humidity of 65% for a minimum of two weeks. The dimensions of the samples were measured with a digital caliper and weights were determined in order to obtain the weight density values (ρ_{12}, at 12% RH). Longitudinal MOE and MOR were determined by a four-point bending test (Kučera 1992) according to Saranpää and Repola 2001. Load was applied in the tangential direction with a modified Lloyd universal testing machine (England).

2.5 Statistical Analysis

Statistical significance of differences in the annual ring and latewood widths and densities between the sites and between the clones was analysed with an analysis of covariance using a mixed model in a statistical program SPSS for windows version 13 (cf. Jaakkola et al. 2005). The results were considered at significance levels $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$. The significance level in pair-wise comparisons between the three sites and between the three clones was $p \leq 0.05$. The strength properties (MOE and MOR) of clones were compared with a one-tail Student's t-test.

3 Results

The average tree diameters (including bark) and tree heights are listed in Table 1. The annual ring width and weight density were measured from near the pith to close to the bark from the 44 stems at breast height (Table 1). The average annual ring width was 3.15 ± 1.32 mm and the latewood proportion was 14.12 ± 7.34% in this material. The annual growth increments of clones are presented sitewise in Fig. 2. The mean annual ring density was 0.461 ± 0.077 g cm^{-3}, the latewood density was 0.750 ± 0.125 g cm^{-3} and the earlywood density was 0.415 ± 0.070 g cm^{-3}. The annual density variation of clones on the three sites is presented in Fig. 3. The effect of site on the whole annual ring

Table 1. Wood characteristics of the cutting clones (A, B and C) growing on the three different sites Loppi (1), Imatra (2) and Kangasniemi (3). The measurement results (one width and density profile measurement per annual ring, from pith to bark) are arithmetic means with a standard deviation in parenthesis. Different letters (a, b and c) mean statistically significant ($p \leq 0.05$) differences between the clones and between the sites. The number of trees: Clones A, B and sites 1, 2: n = 15; clone C and site 3: n = 14; all trees: n = 44. The number of annual rings: n = 843.

	Diameter of tree at 1.3 m mm	Diameter of tree at 6.0 m mm	Height of tree m	First living branch whorl m	Ring width mm	Latewood %	Ring density g cm^{-3}	Latewood density g cm^{-3}
Clone A	137.4 (25.3)	98.2 (22.6)	12.54 (1.21)	2.87 (1.81)	3.24 (1.31) ab	14.93 (6.88) b	0.465 (0.074) b	0.758 (0.125) b
Clone B	123.3 (26.5)	78.5 (28.8)	11.29 (2.24)	2.57 (1.73)	2.92 (1.36) a	15.34 (8.33) b	0.486 (0.082) b	0.776 (0.127) b
Clone C	130.6 (21.4)	85.2 (19.3)	11.31 (1.44)	2.43 (1.25)	3.30 (1.25) b	11.80 (6.05) a	0.428 (0.062) a	0.711 (0.113) a
Site 1	140.3 (25.4)	101.7 (20.9)	12.80 (0.98)	3.24 (0.93)	3.70 (1.22) a	13.29 (7.78) a	0.426 (0.049) c	0.708 (0.092) b
Site 2	143.9 (12.0)	98.1 (12.0)	12.55 (0.78)	3.73 (1.25)	3.00 (1.42) b	14.33 (7.49) a	0.462 (0.075) b	0.750 (0.126) b
Site 3	105.4 (13.1)	60.5 (16.6)	9.67 (1.37)	0.79 (0.53)	2.76 (1.07) b	14.71 (6.57) a	0.497 (0.087) a	0.795 (0.138) a
Mean	130.4 (24.7)	87.4 (24.9)	11.72 (1.76)	2.63 (1.59)	3.15 (1.32)	14.12 (7.34)	0.461 (0.077)	0.750 (0.125)
Maximum	186.0	147.0	14.20	5.60	8.04	62.06	0.743	1.153
Minimum	85.0	36.5	7.80	0.20	0.40	1.90	0.213	0.294
Median	131.3	91.5	12.25	2.75	3.07	12.50	0.458	0.753

width was statistically significant ($p \leq 0.001$) but it did not have significant influence on the latewood proportion of the growth ring. The effect of site on both the annual ring density and latewood density was significant ($p \leq 0.001$). Differences between the sites were tested at the level $p \leq 0.05$ and significant distinctions were marked with letters a, b and c (Table 1). The mean annual ring width was the greatest and the wood density was the lowest on the fertile site 1. The ring width of wood on site 1 deviated from that of the site 2 and site 3. The medium fertile site 3 produced slow-grown wood the density of which deviated from that of wood grown on sites 1 and 2. The difference in the ring density between the sites 1 and 2 was also significant at the level mentioned above.

The effect of clone on both the annual ring width and the latewood proportion was statistically significant at the levels of $p \leq 0.05$ and $p \leq 0.001$, respectively. The influence of clone on the density of annual ring and latewood was also significant ($p \leq 0.001$) (Table 1). The slowest growth rate, the highest latewood proportion and highest density was found in the clone B, the annual ring width of which was significantly narrower than that of the clone C (Fig. 2). The growth rate was the highest in the clone C, the latewood proportion and wood density of which was significantly lower than that of the clones A and B (Figs. 2 and 3).

The mechanical strength properties of wood described by the MOR and MOE are presented in Table 2 and Fig. 4. The average MOR was 67.51 ± 11.50 MPa, MOE was 9.88 ± 1.43 GPa and weight density of the test samples (ρ_{12}) was 414 ± 44 kg m^{-3} in mature wood. The results were determined from the 43 stems (one sample was omitted due to a knot in the middle of sample). The results were compared pairwise between the sites and between the clones at the level $p \leq 0.05$ and the significant differences were marked in Table 2. The MOE and MOR values of clones are presented treewise as a function of weight density on the three sites in Fig. 4. The strength properties were the best on the medium fertile site 3, which produced wood with the highest weight density. The worst mechanical properties were found in the rapidly-growing clone C with the lowest weight density. Clone B had the best density and strength properties but they did not have statistical significance in this comparison. Clone A was intermediate in properties and between clones B and C. MOE showed more variation and had weaker linear correlation ($R^2=0.47$, $n=43$) with density than MOR ($R^2=0.76$, $n=43$).

The site × clone interaction had a statistically significant influence on the annual ring density ($p \leq 0.05$) and the latewood density ($p \leq 0.01$) but not on the growth rate. The annual variation in ring width, latewood proportion, ring density and latewood density was significant ($p \leq 0.001$). The annual ring density (Fig. 3) and latewood proportion (Fig. 2) was low close to the pith and increased reaching the maximum on the average at ring 3 in the juvenile wood and decreased towards the mature wood reaching the minimum at ring 11 from the pith. The ring density and latewood proportion increased again towards the bark. Correlations between the annual ring width and annual ring density and between the latewood proportion and latewood density were non-linear. On site 1 the density of the first rings in the juvenile wood was very low though the latewood proportion was high (Fig. 3). The large density variation between the individual stems is seen in Fig. 4, in which the points representing the individual stems are widely distributed.

Table 2. Modulus of elasticity (MOE) and modulus of rupture (MOR) of the clones (A, B and C) growing in Loppi (1), Imatra (2) and Kangasniemi (3). The measurement results (one measurement per tree, from mature wood) are the arithmetic means with the standard deviation in parenthesis. The letters (a and b) mean statistically significant ($p \leq 0.05$) differences in the strength properties of wood between the clones and between the different growing environments. The number of trees: Clone A, C: $n=14$; clone B and sites 1, 2: $n=15$; site 3: $n=13$; all trees: $n=43$.

	MOE	MOR	Weight density of test samples (ρ_{12})
	GPa	MPa	kg m^{-3}
Clone A	9.89 (1.24) b	68.22 (11.39) b	417 (38)
Clone B	10.60 (1.61) b	73.96 (10.45) b	441 (43)
Clone C	9.11 (1.01) a	59.89 (8.29) a	380 (30)
Site 1	9.63 (1.47) b	63.20 (9.01) b	403 (29)
Site 2	9.50 (0.94) b	64.52 (7.12) b	386 (22)
Site 3	10.62 (1.64) a	75.94 (14.05) a	456 (49)
Mean	9.88 (1.43)	67.51 (11.50)	414 (44)
Max.	12.47	97.65	533
Min.	6.96	40.42	340
Median	9.99	67.05	408

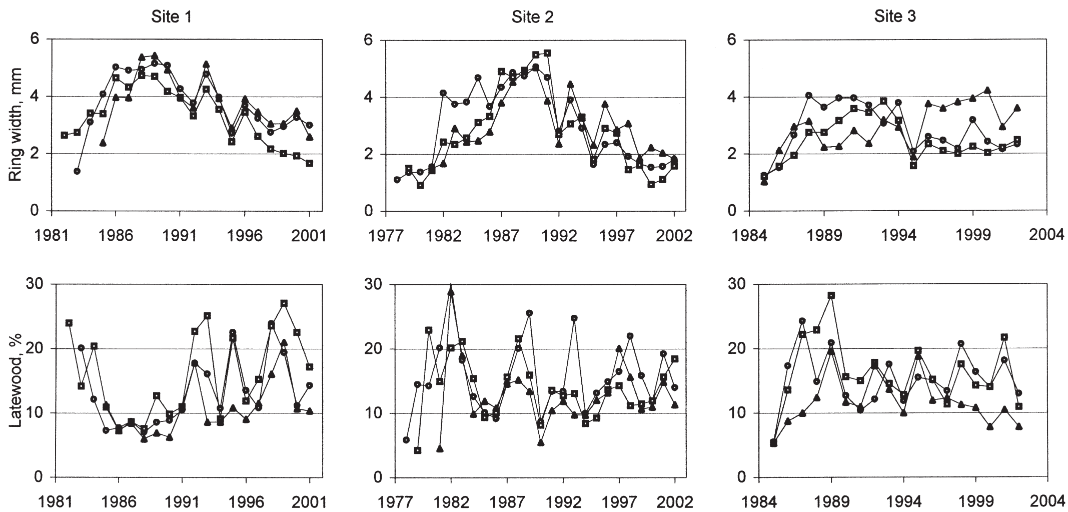

Fig. 2. Annual ring widths and latewood proportions of the cutting clone A (○), clone B (□) and clone C (△) growing on site 1 (Loppi), site 2 (Imatra) and site 3 (Kangasniemi). The statistically significant ($p \leq 0.05$) differences between the clones and between the sites have been marked with the different letters in Table 1.

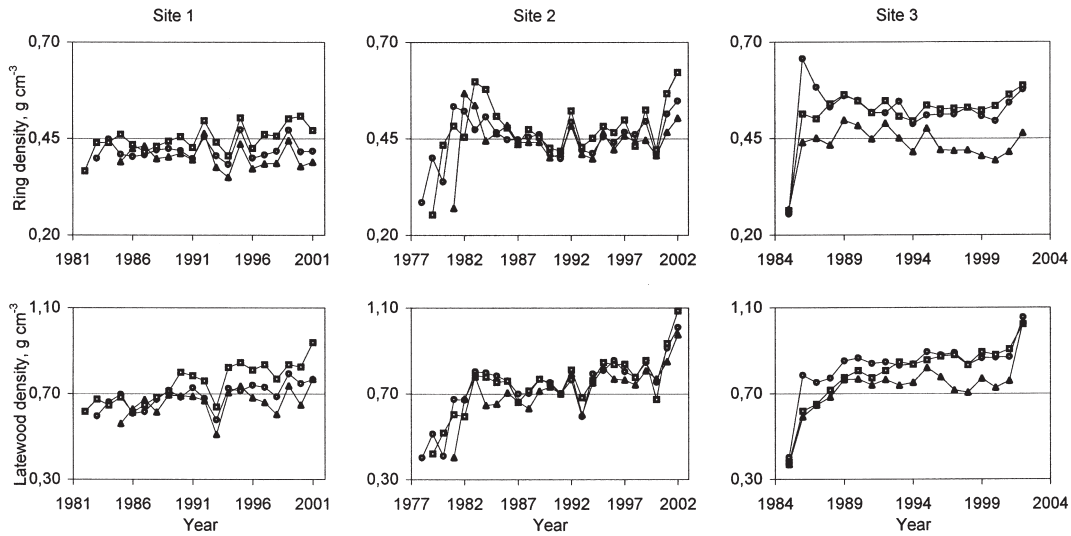

Fig. 3. Annual ring and latewood density of the three clones A (○), B (□) and C (△) from Loppi (1), Imatra (2) and Kangasniemi (3). The significant ($p \leq 0.05$) differences between the clones and between the sites have been marked in Table 1.

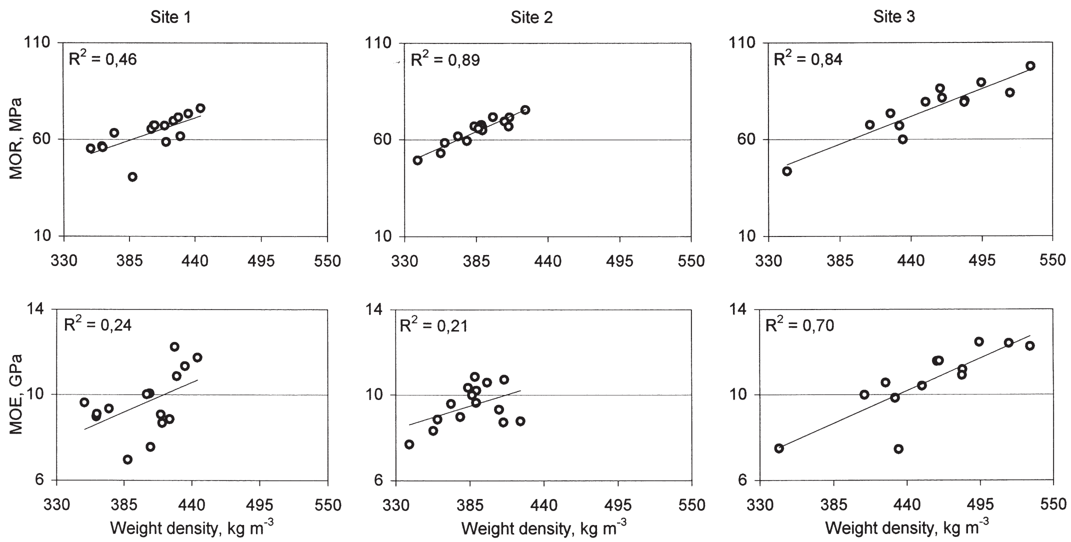

Fig. 4. MOR and MOE values of the clones growing on sites 1 (Loppi), 2 (Imatra) and 3 (Kangasniemi) presented by trees as a function of weight density of the test samples (ρ_{12}). The mean MOR, MOE and ρ_{12} values are presented in Table 2.

4 Discussion

The purpose of Norway spruce cloning in the 1970's was to increase the growth rate of trees. The mother trees for the cutting clones (A, B and C) of this study were selected according to good stem form and fast growth rate. However, growth rate and stem development most probably vary in different environments. Thus, the clones were planted in different locations and sites of varying fertility.

The site, the clone and the site × clone interaction had a significant influence on the annual ring density and the latewood density and this may be due to different abilities of the clones to adapt to the environmental conditions. Although wood density is affected by the environmental and genetic factors, it is known that most growth and wood quality traits have shown low genotype by environment interaction (Hannrup et al. 2004). In this study the latewood proportion of the annual rings was affected especially by the clone (genetic factors). However, the genetic variation does not come out reliably in the limited material of only three clones and tree-to-tree variation within a clone was also fairly large. The annual variation of growth rate and wood density of the material studied was high because of changes in weather conditions (temperature and rainfall) during the growth period. Growth rate has also been found to have some effect on the cell diameter and length in Norway spruce (Mäkinen et al. 2002a). In Norway spruce the basic density varies within the stem between the juvenile wood (about the first 10 rings) and mature wood from the pith to the bark and does not correlate linearly with the annual ring width (Mäkinen et al. 2002b, Saranpää 2003). The basic density has been found to be slightly higher close to the pith than further out (Saranpää 1994). This was true for all clones growing on the sites 2 and 3. However, site 1 was different. The basic density was at the same level from the pith outwards even though ring width behaved in a similar way in all sites (Fig. 3).

The effect of site on the whole annual ring width was statistically significant but it did not have significant influence on the latewood proportion. The effect of site on both the annual ring density and latewood density was significant. Highest density was found in site 3 where growth rate was also the lowest. It is generally believed that rapid growth rate results in low density and lower mechanical strength properties of wood but some exceptions have been reported (Saranpää 2003). Growth rate influences wood density because of the changes in the relative proportions of secondary cell wall and void volume (e.g. cell lumen) (Mäkinen et al. 2002b, Saranpää 2003) and in the relative amounts of chemical components of the cell wall (Saikku 1975).

In this study, the average MOR was 67.5 MPa, MOE was 9.9 GPa, and weight density of the test samples (ρ_{12}) was 414 kg m^{-3} in mature wood, which is well in accordance with earlier results. The mean MOR of *Picea abies* grown in northern Norway has been reported to be 67.7 MPa and the weight density 410 kg m^{-3} (Okstad and Kårstad 1985). The average MOR of mature Norway spruce wood is 82.3 MPa, the MOE 12.6 GPa, the weight density 462 kg m^{-3} and the ring width 2.3 mm in trees growing in monoculture or mixed with birch in Finland, Sweden and Norway (Saranpää and Repola 2001). The highest MOR (75.9 MPa) and MOE (10.6 GPa) were recorded on the medium fertile site 3, which produced wood with the highest weight density (456 kg m^{-3}) and showed the lowest growth rate. MOE showed more variation (Fig. 4) and had weaker correlation ($R^2 = 0.47$, $n = 43$) with density than MOR ($R^2 = 0.76$, $n = 43$), which is in accordance with earlier studies ($R^2_{MOE} = 0.48$, $R^2_{MOR} = 0.79$) (Saranpää and Repola 2003).

5 Conclusions

The effect of site on the annual ring width, the annual ring density and latewood density was statistically significant ($p \le 0.01$) but it did not have significant influence on the latewood proportion of growth rings. The effect of clone on the annual ring width ($p \le 0.05$), the latewood proportion, and the density of annual ring and latewood was significant ($p \le 0.001$). The site*clone interaction had an influence on the annual ring density ($p \le 0.05$) and on the latewood density ($p \le 0.01$) but not on the growth rate. The annual variation in growth and density was significant ($p \le 0.001$). On the basis of this clonal material it can be said that the environment had a large effect on the parameters measured and the three clones differed from each other similarly in the different sites, e.g. the fastest growing clone was fastest on all sites. However, the large differences between individual stems show that it is difficult to predict the wood properties based on the genetic background due to the effects of environment and climate in long-rotation northern forestry.

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