RADIAL DISTRIBUTION OF HEARTWOOD EXTRACTIVES AND LIGNIN IN MATURE EUROPEAN LARCH

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ABSTRACT

For exterior applications high proportions of heartwood are desired, which are normally found in older trees. Extractive and lignin contents are believed to change across the radius, but only a few reports exist on this issue, especially on mature trees. In total, 27 mature and dominant European larch trees (*Larix decidua* Mill.) were harvested from a 146-year-old and a 250-year-old forest site in Austria and France, respectively. The radial trends for extractive contents were linear to slightly curvilinear from the pith to the heartwood-sapwood boundary. The content of acetone extractives and phenolics increased between 1.2% and 2.2% per 100 years, while the hot-water extractive content increased about 5% per 100 years. Phenol and acetone content doubled within 10 cm of radius, while hot-water extractives took between 20–30 cm to double the concentration. Correlation coefficients between ring width and extractive content changed with cambial age, showing positive relationships in the first growth phase but turning around to negative ones at ages over 100 years. Juvenile-mature correlations illustrated a potential to determine extractives and lignin in mature wood through analysis of juvenile wood.

Keywords: *Larix decidua* Mill., phenolics, acetone soluble extractives, hot-water extractives, within-tree variability,

INTRODUCTION

The best-known and most studied within-tree variability in wood is the change from the pith to the bark. Most reports on radial changes are concerned with specific gravity (Zobel and van Buijtenen 1989; Woodcock and Shier 2002), but many other properties have also been considered. In softwoods, radial profiles were investigated for anatomical characteristics (e.g., tracheid length, microfibril angle, ray height), physical and mechanical properties (e.g., wood density, strength, elasticity), and chemical constituents. The latter include cellulose (Wardrop 1951), lignin (Erickson and Arima 1974), hemicellulose (Westermark et al. 1988), extractive components (McMillin 1968; Nault 1988; Stringer and Olson 1987), inorganic elements (McMillin 1969), cation binding capacity (Momoshima and Bondietti 1990) and crystallinity (Wellwood et al. 1974).

Heartwood extractives are formed *in situ* at the sapwood-heartwood boundary (Saranpää and Piispanen 1994; Hillinger et al. 1996) and play a prominent role in the decay resistance against fungi (Eaton and Hale 1993). In larch, the heartwood contains appreciable amounts of arabinogalactan, usually 5%–30% (Côté et al. 1966), and up to 3.5% flavonoids (Babkin et al. 2001). Arabinogalactan, a water-soluble, heavily branched polysaccharide, and the flavanoid dihydroquercetin (taxifolin) were found as the two

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most important extractives in all larch species (Giwa and Swan 1975; Hegnauer 1962). High variability was reported for the amount of heartwood extractives in larch (Dix and Roffael 1997; Srinivasan et al. 1999; Gierlinger et al. 2002a) and a strong relationship between decay resistance and extractive content (Windeisen et al. 2002; Gierlinger et al. 2004).

For exterior applications high proportions of heartwood are desirable, normally reached only in older trees. However, within-tree variability of extractives might be high in old-grown trees, but only a few studies have looked at this question in more detail. Nault (1988) published radial distributions of thujaplicins in some overmature red cedar trees (between 260 and 700 years old). In larch trees Keith and Chauret (1988) looked at radial trends for extractives, but trees were only 28 years old. The present study reports on the radial distribution of different extractive components and lignin of old European larch trees grown at higher elevation. Correlations between extractives and ring widths are shown across trees for different cambial age groups, as well as juvenile-mature correlations of each parameter.

MATERIALS AND METHODS

For this study 27 mature, dominant European larch trees (*Larix decidua* Mill.) were harvested from two forest sites. The Austrian site, "Langau," is part of the northern limestone Alps, situated in Lower Austria at an elevation of 1050 m above sea level. (47°49′ 40″N, 15°09′50″E). The forest site was a pure stand of European larch, grown on a rendzina soil type. Annual rainfall is 1742 mm and mean annual temperature is 8°C. The second site, "Montgenévre," was located in the French "Haut Alpes," at 1750 m above sea level (44°56′N, 6°44′E); precipitation per year is 714 mm, and mean temperature is 7.6°C. European larch trees were growing on brown acidic-soils on moraine ground. All trees were harvested in 1999. A 2-m log was cut from each tree at breast height, and samples were prepared from the central boards. On sanded cross-sectional surfaces, ring widths were measured to the nearest 10 μm using a linear measuring table. For the chemical analyses, blocks that each contained 25 growth rings, clear from knots and resin pockets, were prepared along the radius from the pith to the heartwood-sapwood boundary (Langau: 17 trees, 85 blocks with 25 rings each; Mongenévre: 10 trees, 90 blocks with 25 rings each). The inner part (ring 1-25), containing the juvenile wood (first 15 rings in larch, Keith and Chauret 1988) is referred to as the "juvenile part," and the outer prepared blocks as "mature wood." Samples were dried at 50°C and ground in a cutting mill (Retsch SM1) to pass a 200-μm screen (wood meal). An analytical sieving apparatus (Retsch AS 200 basic) was used to further separate the fraction below 100 μm (wood powder). Near-infrared spectra were collected and the amount of acetone (ACE) and hot-water-soluble extractives (HWE), phenolic substances (PHE), and lignin (LIG) were measured using the methodologies and models outlined elsewhere (Gierlinger et al. 2002b, 2003).

The SPSS 11.0.1 software package was used for statistical analysis. Linear Regressions were used, estimating the coefficients of the linear equation, involving one independent variable (cambial age, radial distance from pith), that predicts the value of the dependent variable (extractive contents). Changes of extractive and lignin content per 100 years and per 100-mm radius were calculated as well as years and radial distance to double concentration to express the radial increase in more meaningful figures. Pearson Correlation was used to measure the linear association between extractive content and ring width, and between the extractive contents of different cambial ages (juvenile-mature correlation).

RESULTS

The trees from Montgenévre were 250 years old (CV=10%), compared to 146 years (CV=3%) at Langau. The descriptive statistics in Table 1 illustrate the great variability found on both sites. The mean ring width at Montgenévre (0.76 mm) was half that at Langau (mean = 1.43 mm). This was due to the greater age of the trees, elevation of the site, and the periodic infestation of larch bud moth (*Zeriaphera diniana* G.N.). The smallest and widest rings were found in the Langau trees. This is reflected in the high coefficient of variation (71%). Minimum, maximum, and mean values for acetone- (ACE) and phenolic- (PHE) extractive contents did not differ appreciably between sites, whereas considerably more hot-water extractives (HWE) were removed from the heartwood of the Montgenévre trees (Table 1). Average lignin content (LIG) was on both sites the same, with CVs of 6% and 8% (Table 1).

Figure 1 presents the radial trends in chemical content with cambial age and radial distance. Trees from both sites reached approximately the same stem diameter (700 mm), although trees from Langau were much younger. Extractive contents exhibited radial increases (Fig. 1A–F). Lignin of the Langau trees increased with the radius and plateaued to a cambial age of about 50 years and then became constant (Fig. 1G). In the Montgenévre trees, LIG peaked in the 126–150 years age class and then declined (Fig. 1H).

Linear regressions were fitted with each extractive content as dependent-variable, and with cambial age and radial distance from pith as independent-variable. Due to its lack of linearity, lignin was excluded from this analysis. Models with cambial age and radial distance showed similar coefficients of determination and regression coefficients (Tables 2 and 3). At Langau, cambial age explained 44% of ACE (Table 2), radial distance explained 49% (Table 3). At Montgenévre, higher coefficients of determination (R2 = 0.61–0.63) were found for ACE as well as PHE (Tables 2 and 3). Hot-water extractives showed the poorest fit with only 19% (Langau) and 31% (Montgenévre) explained by cambial age; and 17% and 30% explained by radial distance (Tables 2 and 3).

To describe the radial increase more meaningfully, the time or distance in which the extractive contents doubles and the changes per 100 years and per 100 mm radius were calculated. The ACE and the PHE increased between 1.2% and 2.2% per 100 rings at the two sites. This is equivalent to 104 and 176 rings, respectively, to double extractive concentration (Table 2). Hot-water-soluble extractives increased by 4.8 % (Langau) and 5.0 % (Montgenévre) per 100 years, time to double concentration was 242 years for Langau and 286 years for Montgenévre. Changes in extractive contents with radial distance showed a similar pattern (Table 3). Phenolic substances doubled within the shortest distance, every 89 mm (Langau) and 66 mm (Montgenévre), followed by ACE, 134 mm and 111 mm, and at least HWE, every 242 mm and 286 mm (Table 3).

Correlation coefficients between ring width and extractive contents were calculated among trees within every age-class to exclude the effect of the radial age trend (radial increase of extractives and decrease of ring width from pith to heartwood-sapwood border). A clear age pattern is visible for this relationship (Fig. 2): While in the first growing years ring widths were positively correlated with ACE and PHE, this relationship became negative by the cambial age of 100 years. Correlations between PHE and ring width were significant in the first two cambial age groups (ring 1-25, ring 26-50) with a correlation coefficient higher than 0.32 (Fig. 3).

Correlations between the chemical content of the inner block and the chemical content of the more distant heartwood blocks (juvenile-mature correlations) are shown in Fig. 3 for lignin and the three extractive types. All four chemical groups gradually reduced their correlation with distance from the juvenile phase (rings 1-25). Hot-water-soluble extractives of the inner part (ring 1 to 25) correlated best with the contents of the following parts; even with the contents in the 100 rings distant part correlation coefficients were above 0.6 (Fig. 3). Strength of correlation between ACE and PHE of the inner part and of the following cambial age groups declined by about 0.2 every 25 years. This illustrates the potential to conclude from chemical contents in the inner part on the chemical contents of the outer part of the wood, to predict chemical parameters of mature wood through analysis of juvenile wood.

DISCUSSION

Wood properties vary with age from the pith outward to the bark. According to Panshin and

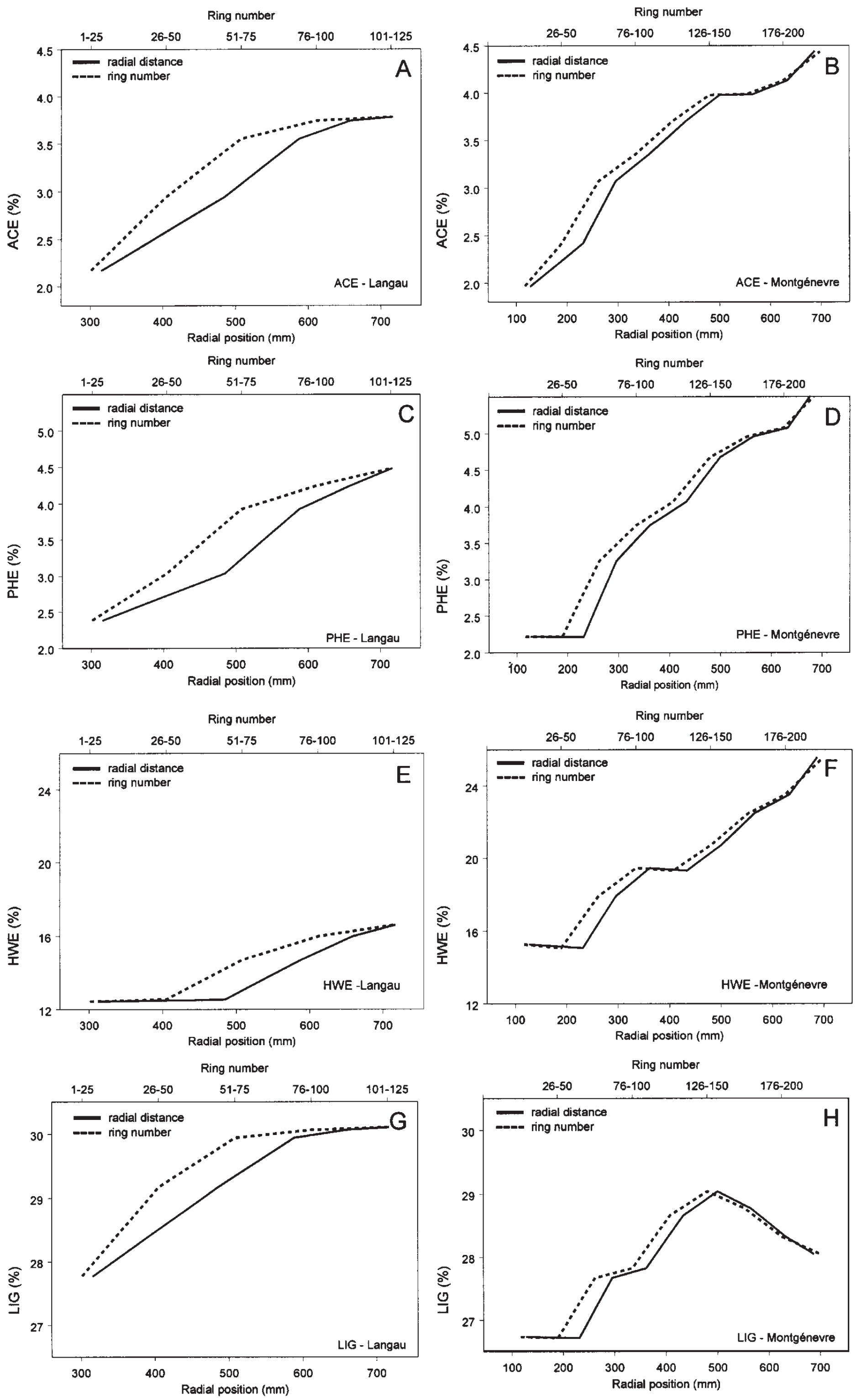

FIG. 1. Radial trends for acetone-soluble extractives (A,B), phenolic extractive (C,D), hot-water extractives (E, F), and lignin (G,H) for European larch grown in the Austrian (Langau) Alps (left side) and the French (Montgenévre) Alps (right side).

TABLE 1. *Descriptive statistics (min, max, arithmetic mean, and coefficient of variation CV) for age, ring width, extractive types (ACE = acetone-soluble extractives, HWE = hot-water-soluble extractives, PHE = total amount of phenolic substances) and lignin (LIG) of the sites Langau (Lang) and Montgenèvre (Mont).*

	Minimum		Maximum		Mean		CV (%)	
	Lang	Mont	Lang	Mont	Lang	Mont	Lang	Mont
AGE (years)	139	188	206	275	146	250	3	10
Ring width (mm)	0.19	0.22	4.11	2.11	1.43	0.76	71	44
ACE (%)	1.2	1.4	5.3	5.1	3.3	3.4	27	28
HWE (%)	7.0	9.1	24.6	32.0	14.4	19.4	26	28
PHE (%)	1.3	1.5	7.0	6.6	3.6	3.8	35	36
LIG (%)	25.5	21.7	34.9	30.9	29.4	28.0	6	8

TABLE 2. *Regression analysis of radial trends for acetone-soluble (ACE), hot-water soluble (HWE) and phenolic (PHE) extractive contents in larch heartwood, as a function of cambial age. Coefficient of determination (R^2), regression coefficients (Reg.Coeff) are shown. The change in extractive contents are given per 100 year increments; along with the period in years to double the concentration.*

Site		R^2	Reg.Coeff.	Change per 100 years	Years to double concentration
Langau	ACE	0.44	0.66	1.7	134
	HWE	0.19	0.44	4.8	242
	PHE	0.37	0.61	2.2	104
Montgenèvre	ACE	0.61	0.78	1.2	176
	HWE	0.31	0.56	5.0	286
	PHE	0.63	0.79	1.8	111

TABLE 3. *Regression analysis of radial trends for acetone-soluble (ACE), hot-water-soluble (HWE) and phenolic (PHE) extractive contents in larch heartwood, as a function of radial distance from pith. Coefficient of determination (R^2), regression coefficients (Reg.Coeff) are shown. The change in extractive content is given per 100-mm radius and the radial distance to double concentration.*

Site		R^2	Reg. Coeff.	Change per 100 mm of radius	Radial distance to double concentration (mm)
Langau	ACE	0.49	0.70	1.4	118
	HWE	0.17	0.41	3.5	294
	PHE	0.38	0.62	1.7	89
Montgenèvre	ACE	0.62	0.79	1.7	109
	HWE	0.30	0.55	6.9	194
	PHE	0.63	0.79	2.5	66

de Zeeuw (1980), age-related wood specific gravity variation in conifers can be categorized in three general patterns (types). In the pattern exhibited most commonly in many *Larix* and *Pinus,* and occasionally in *Picea* species, the wood specific gravity increases from the pith to the bark in a linear or curvilinear trend, flattening in the mature section. This trend may exhibit a slight decrease in the outer rings of overmature trees. In a second trend, specific gravity decreases in its early formation, and then increases until the mature period is reached; and in the third trend mean specific gravity is higher at the pith than at the bark, decreasing either in a straight line or in a curve. Variation in chemical composition within trees is investigated on

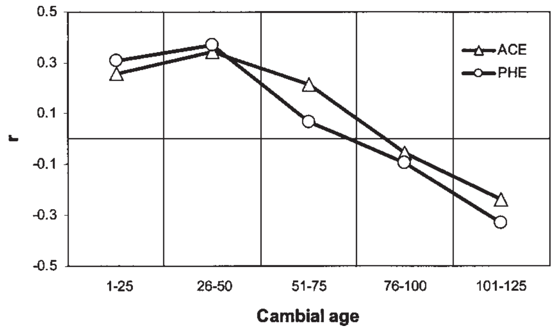

FIG. 2. Correlation coefficients (r) between ring-width and extractive contents (ACE = acetone-soluble extractives, PHE = phenolic extractives) at different cambial age. ($n=27$, $p<0.05$, $r=0.32$)

fewer species, and no trend patterns are distinguished. Our trends for ACE and PHE were linear to slightly curvilinear from the pith to the heartwood-sapwood boundary (Fig. 1A–D), which would be close to the first described trend in specific gravity. The HWE was constant in the first growing period (Fig. 1E–F), before it steadily increased until the sapwood-heartwood border. Unlike specific gravity, the extractives did not show a flattening at mature age. This is also confirmed by Nault (1988), who looked at radial trends of ethanol-benzene extractive content and thujaplicin content in western red cedar. The trends are similar to the one we obtained with larch; the extractive contents of the two old-growth western red cedar trees (600 years) did not become constant with age. This indicates, at least for larch and western red cedar, that extractives may continue to build up in concentration radially for rather long periods. In McMillin's (1968) analysis of fast-grown loblolly pine (*Pinus taeda* L.), alcohol-benzene soluble extractive content decreased with increasing distance from pith; and in Keith and Chauret's (1988) analysis in fast-growing larch, they remained relatively constant. In Douglas-fir, Erickson and Arima (1974) reported a constant concentration of extractives in the first 10 tree-rings from the pith, followed by a decline towards the heartwood-sapwood boundary. However, the trends of these investigations extended over only 16 to 25 rings, which explains the differences with our results.

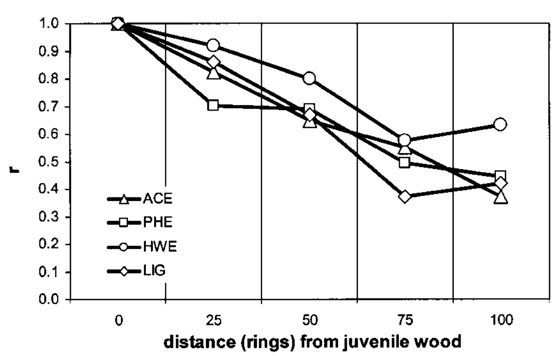

FIG. 3. Juvenile-mature correlation (= correlation between the inner part and the more outer parts) for extractive contents (ACE = acetone-soluble extractives, PHE = phenolics, HWE = hot-water-soluble extractives) and lignin (=LIG) in European larch (r = correlation coefficient, 0 = juvenile wood = ring 1-25).

The lignin trends in the old larch trees showed a radial increase too, but not till the heartwood-sapwood border (Fig. 1G,H). Lignin was constant in the last 20 years of the Langau trees (Fig. 1G) and declined in the last 75 years of the older Montgenévre trees (Fig. 1H). Ericksen and Arima (1974) reported a decreasing trend with cambial age for Douglas-fir; however, trees were only 27 to 31 years of age. Kreft (1983) showed that lignin content was higher in more mature specimens of old-grown western red cedar, and Kramer and Kozlowski (1979) indicated that the wood of over-mature trees may have higher lignin contents.

A higher phenolic content goes hand in hand with higher decay resistance in larch heartwood (Gierlinger et al. 2004). Due to the strong changes in extractive contents in the radial direction, with phenolic extractive content doubling within 100 tree-rings, the natural durability in larch may show radial trends in mature larch trees. This seems opposite to the finding by Gartner et al. (1999), who found no such trend for Douglas-fir. However, the trees in the latter study were only 34 years old. It should be emphasized that radial age-trends in trees might be different between studies because of different tree age and number of rings per analyzed radial increment. Generalization of radial trends needs to state clearly the number of rings included in the data. In larch heartwood, brown-rot decay resistance was described as highly variable, ranging from non-durable to moderately durable (Morell and Freitag 1995; Viitanen et al. 1997; Srinivasan et al. 1999; Jacques et al. 2002). In our study, the age of the wood and the radial position were shown to contribute to variability of heartwood extractives in larch, and consequently to variable decay resistance.

For investigation of the growth rate on extractive contents, correlations between ring width and extractive contents were calculated separately within each cambial age class. For larch heartwood, changing relationships across the radius between ACE, PHE, and growth rate were shown (Fig. 2). While a positive relationship existed in the first two groups (1-25 rings, 26-50 rings, respectively), the relationship disappeared and became significantly negative for the 101–125 years group. These results suggest that faster growth during the first growing phase is associated with more PHE and ACE in the corewood; at higher cambial age, this relationship disappears or becomes negative.

Finally, juvenile-mature correlations for extractive and lignin contents are shown for 100 rings starting with the first 25 growth rings. In the general context of early selection in forest trees, investigating juvenile-mature correlation is important. In tree improvement studies, genetic juvenile-mature correlations have been determined for many traits, but not for extractives or lignin (Lambeth 1980; Gill 1987). Positive correlations between the investigated cambial age groups of these old trees suggest that further investigations on age-age correlations might be of benefit for early selection of larch trees with high phenolic content and consequently high decay resistance in tree improvement programs.

CONCLUSIONS

The extractive contents gradually increase from pith towards the heartwood-sapwood border, with no saturation at mature age. Radial variation of extractive contents, especially phenolic substances, may go hand in hand with changes in decay resistance. Therefore the radial position, and cambial age of larch trees may widely determine the decay resistance of larch heartwood. Correlations between extractive contents in the juvenile wood and desirable genetic traits of mature trees may allow better selection of larch trees for high natural durability at an early stage.

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