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Variability of wood properties in two wild cherry clonal trials

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Abstract There has been an increase in wild cherry cultivation over recent decades, revealing a need for improvements in planting material to be used for the production of high quality timber. To date, trial tests have been carried out mainly on growth and tree architectural traits, while no investigations have focused on wood properties. The present study investigated the variability of the growth traits and the physical and mechanical properties of wild cherry wood, both within the tree, within and among clones and between sites. The aims of the study are to provide useful information on the genetics of wood traits in valuable hardwoods and to discuss how within-tree variation can affect early selection of genotypes. The results suggest that site was the most important source of variation in growth traits and in the proportion of heartwood, although differences among clones were highly significant. The number of sapwood rings was very homogeneous both between sites and among clones. Concerning the wood traits, most variation was detected within the tree, rather than within or among clones or between sites. Within tree variability seems to be mainly due to heartwood/sapwood presence. However, since there is a high correlation between heartwood and sapwood properties, a quite

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efficient selection made on the basis of sapwood should provide an efficient means of selecting heartwood traits.

Introduction

Cherry wood is highly appreciated in the Italian industry and it is considered in every respect a valuable timber by the European market. Commonly speaking, it includes wild cherry (*Prunus avium*) but also black cherry (*P. serotina*), imported mainly from North America to meet the high European demand of cherry timber. There has been an increase in wild cherry cultivation over recent decades in Italy as well as in other European countries (Curnel et al. 2003), thanks to public incentives aimed at developing the production of valuable timber in new plantations established on agricultural lands. This increase has revealed a need for the selection and improvement of planting material, to be used in the production of high quality timber. Consequently, numerous wild cherry breeding programmes have been developed in many European countries (Muranty et al. 1998; Santi et al. 1998; Martinsson 2001; Kobliha 2002; Curnel et al. 2003).

In Italy, wild cherry improvement programmes started in the 1980s with the selection of *plus* trees and the establishment of clonal plantations, now available for further studies. To date, selection and the following trial tests have been carried out mainly on growth and tree architectural traits (Ducci et al. 1990; Ducci and Veracini 1990; Minotta et al. 2000), while no investigations have included wood properties, with the exception of wood colour (Signorini 2006; Ducci et al. 2006). Since timber is the final objective of silviculture, studies on the wood properties of clones previously selected on a different basis would appear to be of far greater interest (Nocetti 2008).

The benefits and difficulties of including wood traits in breeding programmes have been widely discussed elsewhere (Rozenberg and Cahalan 1997; Rozenberg et al. 2001; Raymond 2002).

The most widely used trait is certainly wood density, because it is easily measurable (non-destructive methods are possible as well) and because it is commonly considered a key indicator of wood quality and a good predictor of the physical and mechanical properties of wood (Zobel and van Buijtenen 1989). However, although various investigations concerning the genetics of density and the other wood properties of softwood can be found in literature, very little is known about valuable hardwoods (previous studies have focused mainly on *Populus* and *Eucalyptus*) (Zobel and Jett 1995).

Moreover, in order to reduce the time of the breeding programmes, the selection phase is usually carried out on young trees, but the final product (wood) is affected by strong within tree variability due to many factors, including cambial age, growth rate and heartwood formation (Zobel and van Buijtenen 1989). Therefore, it is crucial for the breeders to be aware of the major causes that affect wood variability and the consequences they have on the genetic parameters.

Hence, the aim of the present study is to investigate the variability of the growth traits and some physical and mechanical properties of wild cherry wood, both within tree, within and among clones and between sites. The aims of the study are to provide useful information on wood trait genetics in valuable hardwoods and to discuss how the within-tree variation can affect the early selection of genotypes.

Materials and methods

Site description

A total of 71 wild cherry trees were sampled in two 20-year old clonal plantations, belonging to the experimental network of the CRA (Council for Research on Agriculture)-Research Centre for Silviculture of Arezzo (CRA-SEL).

The first site is located on the "Marani" farm, some kilometres north of Ravenna, in the Po Valley, north-central Italy and the second (Forestello) is located about 40 km south of Florence, in central Italy (Table 1).

The "Marani" farm site (in the following named Marani site) lies 2 km from the Adriatic coast. It is characterised by north-easterly prevailing winds, partially sheltered by stone pine wind-breaks. The transplants were established at a 3 m × 3 m spacing in 1986 and systematically thinned in 1995.

At the Forestello site, instead, where the soil is poor in nitrogen and phosphorus, the cherry clones were planted in 1987, mixed with an Italian alder (*Alnus cordata*) nurse in order to improve nutrition by exploiting the nitrogen-fixing ability of alder. Spacing was 3 m × 3 m between trees, but 6 m × 6 m between wild cherry trees (Ducci et al. 1990, 2006). No thinning was performed at this site. Today, from a silvicultural point of view, the plantation has a two-layer structure, where the dominant layer is wild cherry. Following a very fast initial growth phase, the Italian alder served its purpose at around the tenth year, and is at present declining.

Clonal materials

The clones were micro-propagated from selected phenotypes by the Forest Genetic Resources Laboratory of CRA-SEL. The clone provenance is the central Apennines

Table 1 Site characteristics

Site	Marani	Forestello
Location	lat. 44°27′ N, long.12°12′ E	lat. 43°34′ N, long. 11° 29′ E
Altitude a.s.l.	5 m	250 m
Soil	Silty-loam (64% silt, 27% clay)	Loam (44% silt, 30% clay)
Mean annual T	13°C	14°C
Total annual precipitation	650 mm	870 mm
Spacing	3 m × 3 m, thinned (25%) in 1995	3 m × 3 m mixed, cherry spaced 6 m × 6 m
Age at sampling	20	20
Sampled clones	6	4
Ramets per clone	8	4–7

(Bologna, Florence and Arezzo), between 44°31′20″lat. N and 43°23′00″ at different altitudes (between 150 and 1,000 m a.s.l.).

Phenotypes were selected with scoring methods for their dominance, stem form and branching characteristics (Ducci 2005).

At the Marani farm all 6 clones, 8 ramets per clone, were sampled in spring 2006. Whilst, at the Forestello site, 2 of the 6 clones were not available, so only 4 clones, 4–7 ramets per clone were sampled in spring 2007. The trees were randomly selected from the plantations.

Measurements and laboratory tests

In the following the measured and analysed traits are described. They can be divided into three main groups: growth traits (the characteristics of the standing tree); information on the heartwood and sapwood content; wood traits (the physical and mechanical properties of wood).

After felling, diameter at breast height (dbh) and every 2 m and total height (h) were measured for each tree; from these field measurements the stem volume (vol) was calculated (growth traits).

A 1-m-long log was collected 50 cm above the ground level from each sampled tree and transported to the laboratory, where it was immediately processed.

A 2-cm thick disc was cut from each log and scanned to calculate the percentage area of heartwood on total cross area (HW%) and the heartwood diameter (as an average of two perpendicular diameters, HWd) by means of an image analyzer software; the number of sapwood rings (SR) was also counted (heartwood/sapwood content traits).

The remaining part of the log was used to produce the specimens for wood density, shrinkage and dimensional stability measurements and for mechanical tests (wood traits). Defect-free samples were cut from the four radial planks of the log and numbered in sequence from the pith to the bark. The cambial age and the heartwood/sapwood position were also recorded for each specimen. In order to determine the wood density, maximum shrinkage and dimensional stability, the specimens were first measured in green conditions and then oven-dried. The basic wood density (BD) was intended as oven-dry weight divided by the green volume; the radial (RS), tangential (TS) and volumetric (VS) shrinkages were calculated as a percentage of the green measure; the shape factor (T/R) was the ratio between tangential and radial shrinkage.

For mechanical tests the specimens were cut and conditioned at 65% RH and 20°C prior to the test performance. The modulus of elasticity (MOE) was measured by means of the BING software developed by CIRAD (http://www.xylo-metry.org/en/softwares.html) (Brancheriau and Baillès 2002). Afterwards, the specific modulus of elasticity (sMOE) was calculated as the ratio of MOE to wood density; it can provide information on the woody matter properties (Cilas et al. 2006). The specimens were subjected to static bending test to determine the modulus of rupture (MOR). The maximum compression strength (MCS) parallel to grain and the maximum shear strength (MSS) were calculated as the load at failure divided by the cross specimen area measured at the testing time. Finally, wood hardness (HB) was determined by means of the Brinell method. The specimen size and standards followed for the tests are shown in Table 2.

Tests to determine the physical properties were carried out on 406 and 339 specimens, in Marani and in Forestello, respectively, whilst mechanical tests were performed on 822 and 635 specimens.

Data analysis

The wood specimens were grouped by cambial age. For the physical property determinations, three samples per ray in Marani and four samples per ray in Forestello (and a corresponding number of age groups) were obtained. For the mechanical tests, only two groups were possible. The cambial age groups were also classified according to heartwood or sapwood presence.

An analysis of variance (ANOVA) of the data obtained was then calculated, including all the sources of variation: site (*si*), clone (*cl*, 4 levels), tree-within-clone (*tr/cl*), cambial age (*ca*, 3 levels for physical and 2 for mechanical properties) and all the studied traits ("·" used as symbol of interaction).

$$\text{Data} = \text{mean} + si + cl + tr/cl + ca + si \cdot cl + si \cdot ca + cl \cdot ca + si \cdot cl \cdot ca + \text{error} \quad (1)$$

For the wood traits, all the effects were then studied in depth separately, according to the results obtained. Cambial age means were adjusted at single site level using the following ANOVA:

$$\text{Data} = \text{mean} + cl + ca + cl \cdot ca + \text{error} \quad (2)$$

Then within each site, the variation within and among clones (i.e., intra- and inter-clone) was tested separately for heartwood and sapwood samples by means of the following ANOVA model:

$$\text{Data} = \text{mean} + cl + tr/cl + \text{error} \quad (3)$$

The Pearson correlation coefficients between heartwood and sapwood were then calculated based on tree mean values for all wood traits.

Table 2 Specimen dimensions and standards followed for the wood property tests

Test	Specimen dimension (mm) ($b \times h \times l$)	Standard
Basic density	20 × 20 × 30	ISO 3131
Shrinkages	20 × 20 × 30	ISO 4469
		ISO 4858
Bending MOE	20 × 20 × 400	Dynamic method (BING http://www.xylo-metry.org/en/softwares.html)
Bending MOR	20 × 20 × 400	ISO 3133
Compression	20 × 20 × 30	ISO 3787
Shear	20 × 20 × 20	ISO 3347
Hardness	50 (length)	EN 1534

Finally, an analysis covering both the trials was performed to investigate the inter-site variation of the heartwood and sapwood samples separately using the following model:

$$\text{Data} = \text{mean} + si + cl + si \cdot cl + \text{error} \quad (4)$$

Results and discussion

Descriptive statistics

At Forestello, the trees had greater diameter, height and therefore stem volume than at the Marani site (Table 3). However, the percentage area of heartwood was considerably higher in the stems of the Marani site, where the heartwood diameter was smaller than in Forestello.

Since the climatic conditions were very similar and both locations were defined in previous works as fertile stands (Ducci et al. 2006), the differences between

Table 3 Means, standard errors (SE) and phenotypic coefficients of variation (CV_p) of measured growth and wood characteristics, grouped by site

Trait	Marani		Forestello	
	Mean ± SE	CV_p (%)	Mean ± SE	CV_p (%)
Growth traits				
Diameter at breast height (dbh) (cm)	19.6 ± 0.3	9.8	27.5 ± 0.6	10.0
Height (h) (m)	11.73 ± 0.1	7.6	17.1 ± 0.4	10.3
Stem volume (vol) (dm^3)	177.0 ± 6.4	24.9	426.3 ± 25.4	28.6
Heartwood/sapwood content				
Heartwood area (HW%) (%)	53.5 ± 1.4	18.1	39.1 ± 1.6	19.7
Heartwood diameter (HWd) (cm)	12.9 ± 0.2	10.5	15.3 ± 0.5	16.8
Number of sapwood rings (SR)	10.0 ± 0.2	15.1	10.3 ± 0.2	11.1
Wood traits				
Basic density (BD) (kg/m^3)	493.6 ± 1.4	5.8	497.9 ± 2.0	7.4
Radial shrinkage (RS) (%)	4.4 ± 0.1	27.2	4.7 ± 0.1	19.3
Tangential shrinkage (TS) (%)	10.1 ± 0.1	16.1	11.4 ± 0.1	11.9
Volumetric shrinkage (VS) (%)	14.3 ± 0.1	17.7	15.7 ± 0.1	12.6
Shape factor (T/R)	2.4 ± 0.0	17.2	2.5 ± 0.0	13.2
Modulus of elasticity (MOE) (MPa)	11,341 ± 74	9.1	11,638 ± 75	8.3
Specific modulus of elasticity (sMOE) [$MPa/(kg\ m^3)$]	17.7 ± 0.1	11.2	18.4 ± 0.1	9.6
Modulus of rupture (MOR) (MPa)	111.2 ± 1.0	9.9	114.5 ± 1.1	12.9
Maximum compression strength (MCS) (MPa)	50.2 ± 0.3	10.2	51.6 ± 0.4	10.3
Maximum shear strength (MSS) (MPa)	16.7 ± 0.2	14.1	16.0 ± 0.2	15.2
Hardness (HB) (kg/mm^2)	3.7 ± 0.1	18.1	3.6 ± 0.1	18.0

sites in growth traits and heartwood content can be explained by silvicultural factors: at the Marani site the trees have shown very slow growth rates over the past few years, mainly due to competition for space between trees; at the same time, at Forestello the trees took advantage from the mixture with nitrogen-fixed species (*A. cordata*), increasing their productivity (Kelty 2006). Moreover, the large decrease in growth rate of the Marani trees resulted in very narrow rings in the sapwood zone and, since the number of SR was almost the same at the two sites, it led to a higher percentage area of heartwood in Marani. Again, the generally greater stem diameters of the Forestello trees corresponded to their greater heartwood diameters.

Despite the above comparison, the overall wood traits (physical and mechanical wood properties) were more homogeneous at the two sites. The phenotypic coefficients of variation were quite similar for some traits (i.e. dbh) but differed for others (i.e. heartwood diameter). The basic density showed the lowest coefficient of variation at both sites, though the composition of clones was not identical.

The symbols used in the following text are reported in Table 3.

Overall analysis of variance

The effects and interactions, for most of the variables, were highly significant (Table 4). For the growth and heartwood traits, the greatest effect was noticed for the site factor but significant differences between clones were also found, indicating moderate genetic control. Furthermore, the differences between sites in competitive pressure and nutrition, as already described, could explain the high level of *site* × *clone* interaction, compared to the clone effects.

Other works carried out in clonal trials of wild cherry in Europe have reported similar results: Curnel et al. (2003) in Belgium and Ducci et al. (1990) in Italy found significant differences among sites for both tree height and girth and significant *site* × *clone* interaction.

Moreover, in other works including enough clones to calculate broad sense heritabilities, the clone effect was also highly significant for height and girth, and low-to-medium heritabilities were estimated: 0.11–0.52 and 0.11–0.55 (Curnel et al. 2003), 0.22–0.56 and 0.31–0.70 (Santi et al. 1998).

To the best of the authors' knowledge, no previous studies on the heartwood content of wild cherry clones are available. However, a moderate-to-high genetic control of the percentage of heartwood in black walnut has been reported (Rink 1987; Woeste 2002).

Finally, no significant effect was found for SR. The number of SR was very homogeneous both between sites and among clones, showing low genetic control over this. This is also a first indication (for a limited set of clones) that the growth rate does not influence the number of rings which have already turned into heartwood: i.e. even if trees continue to grow well, transformation of wood occurs at the same speed.

Nelson (1976) found 13.6 as the mean number of SR of black cherry trees of various ages without any significant differences among the five stands studied. This value is slightly more than the result of the present study.

Table 4 *F* values and significance as results of the overall analysis of variance for all the factors (site, clone, tree within clone, cambial age) and their interactions for all the selected traits (for symbol explanations see Table 3)

Trait	Site	Clone	Tree within clone	ca	Site × clone	Site × ca	Clone × ca	Site × clone × ca
dbh	244.6***	5.2**			3.9*			
h	799.9***	21.8***			10.6***			
vol	283.8***	14.4***			10.4***			
HW%	89.1***	11.3***			10.8***			
HWd	36.9***	3.6*			7.1***			
SR	0.8 ns	3.3*			1.4 ns			
BD	99.3**	41.6***	4.6***	201.8***	43.8***	107.1***	3.3**	2.2 ns
RS	183.6***	9.6***	2.4***	882.4***	31.2***	42.5***	1.1	2.7*
TS	935.0***	17.5***	2.8***	1,056.8***	4.8**	20.0***	5.1***	13.8***
VS	717.1***	10.6***	2.6***	1,440.9***	13.2***	40.4***	3.9***	11.3***
T/R	0.7 ns	11.1***	2.1***	124.0***	27.2***	9.6***	1.3 ns	1.3 ns
MOE	31.4***	142.4***	2.4***	10.7**	16.7***	6.0*	2.0	11.6***
sMOE	0.0 ns	48.6***	4.6***	62.0***	25.8***	133.3***	0.6 ns	13.3***
MOR	48.7***	20.2***	1.5*	84.5***	24.6***	4.7*	4.9**	0.2 ns
MCS	78.6***	96.4***	2.0***	391.9***	13.5***	23.3***	4.8**	1.7 ns
MSS	0.0 ns	24.3***	1.1 ns	156.5***	4.4**	21.9***	1.7 ns	0.1 ns
HB	4.1 ns	4.6**	1.3 ns	34.7***	0.6 ns	9.2**	0.8 ns	0.4 ns

* Significant at 5% level

** Significant at 1% level

*** Significant at 0.1% level

ns not significant

Moreover, Savill et al. (1993) found high values of broad sense heritability based on the clone means (0.83) for the number of SR in oak. The contrast with our result can be probably explained by the different species (oak vs. cherry) and by the limited number of clones available in our work.

For the wood traits, tree-within-clone, *clone* × *cambial age* and *site* × *clone* × *cambial age* were comparatively negligible effects. Except for MOE and sMOE, cambial age was the most explanatory factor; indeed, it was even huge for RS, TS, and VS.

In consideration of the comparative importance of interactions of the type *site* × *other effects* which emerged, together with the lack of available information at a multi-site level, more detailed analyses were then done within each site.

Intra-tree variation

In agreement with what other authors affirmed in previous works (Mátyás and Peszlen 1997; Zhang and Jiang 1998; Baillères et al. 2001), in this study, most of the variability of the wood traits was detected within tree rather than within or among clones or between sites.

The within-tree variation of wood properties in the radial direction may be due to many factors and, largely to growth rate (ring width), cambial age and heartwood formation. In particular, the relationship between ring width and wood properties is beyond the scope of this paper and will not be discussed here.

The adjusted means for cambial age were calculated, based on the ANOVA (model 2) results (not shown), except for MOE in Marani (not significant). With the exception of BD, sMOE and HB in Marani, wood traits differed considerably for heartwood and sapwood samples (Table 5) and not for single cambial age groups.

The cambial age affects the wood characteristics because of the juvenile or adult wood formation. The juvenile wood properties vary by species, but they seem much more important in the softwoods than in the hardwoods; in the diffuse porous hardwoods in particular, juvenile wood properties do not differ considerably from the adult wood (Zobel and Sprague 1998). Furthermore, to the best of the authors' knowledge, there are no specific studies on juvenile wood in wild cherry, but the results of several works carried out on hardwood species lead the authors to presume that 20-year old hardwood trees represent mostly juvenile wood (Bendtsen and Senft 1986; Evans et al. 2000; Medzegue et al. 2007).

Therefore, according to the present findings, and for the trees here examined, the most important cause of the within tree variation of wood properties seems to be the heartwood/sapwood presence.

In agreement with the normal trends that characterize the heartwood/sapwood transition (the great amount of extractives increases heartwood's dimensional stability and its wood density—Hillis 1987; Miller 1999; Taylor et al. 2002), the data here showed much higher shrinkage values (radial, tangential and volumetric) in sapwood than in heartwood (respectively, +59%, +32%, +38% in Marani, +36%, +22%, +25% in Forestello). To simplify, in the following text only the results for volumetric shrinkage are shown; similar trends were observed for linear shrinkages.

T/R, contrary to this, was higher in heartwood (+22% in Marani, +12% in Forestello). BD did not show a clear trend in the Marani samples, but in the Forestello trees it decreased from the pith to the bark (-12%) (Table 5).

Moreover, the heartwood zone samples had significantly higher mean values for all the mechanical properties (+8 to +24%), except for MOE and sMOE (Table 5).

During the heartwood formation process, no structural changes occur in the cell walls; therefore, some authors assumed the absence of remarkable differences in strength properties exclusively due to heartwood formation (Panshing and Zeuw 1980 in Taylor et al. 2002). Other authors, instead, hypothesize the influence of the extractives (that are much more abundant in heartwood than sapwood) over the strength properties (Green et al. 1999) and reported a significant decrease in compression strength and transversal MOE, but not in axial MOE after removal of extractives (Grabner et al. 2005).

Table 5 Mean values and standard error (SE) of wood physical and mechanical properties grouped by cambial age (ca) and corresponding to heartwood or sapwood (h/s)

Group	ca	h/s	BD (kg/m^3) Mean ± SE	RS (%) Mean ± SE	TS (%) Mean ± SE	VS (%) Mean ± SE	T/R Mean ± SE
Marani							
1	3–5	h	487.8 ± 1.2b	3.7 ± 0.0a	9.2 ± 0.1a	12.9 ± 0.1a	2.6 ± 0.0b
2	6–8	h	500.9 ± 1.5a	3.7 ± 0.0a	9.2 ± 0.0a	12.8 ± 0.1a	2.5 ± 0.0b
3	9–	s	493.8 ± 1.3ab	5.9 ± 0.0b	12.2 ± 0.0b	17.7 ± 0.0b	2.1 ± 0.0a
Forestello							
1	3–5	h	522.2 ± 1.4a	4.1 ± 0.0a	10.4 ± 0.0a	14.3 ± 0.0a	2.6 ± 0.0b
2	6–8	h	522.3 ± 1.7a	3.9 ± 0.0a	10.2 ± 0.0a	14.0 ± 0.0a	2.6 ± 0.0b
3	9–12	s	483.3 ± 2.8b	5.3 ± 0.0b	12.7 ± 0.0b	17.7 ± 0.0b	2.4 ± 0.0a
4	13–	s	459.2 ± 1.4c	5.6 ± 0.0b	12.5 ± 0.1b	17.6 ± 0.1b	2.3 ± 0.0a*

Group	ca	h/s	MOE (MPa)	sMOE ($MPa/kg/m^3$)	MOR (MPa)	MCS (MPa)	MSS (MPa)	HB (kg/mm^2)
Marani								
1	3–7	h	–	18.0 ± 0.2a	115.5 ± 0.7a	52.3 ± 0.2a	17.4 ± 0.1a	3.9 ± 0.2a
2	8–	s	–	17.4 ± 0.1a*	105.1 ± 0.9b	47.0 ± 0.4b	15.5 ± 0.1b	3.6 ± 0.3a*
Forestello								
1	4–7	h	11,466 ± 61a	17.2 ± 0.1a	121.3 ± 0.7a	55.2 ± 0.2a	17.7 ± 0.1a	3.9 ± 0.0a
2	11–	s	11,794 ± 92b	19.4 ± 0.1b	107.8 ± 0.8b	47.9 ± 0.3b	14.3 ± 0.1b	3.2 ± 0.0b

* Statistically different at 1% significance level

Mean values with the same letter within the column are not statistically different at 0.1% significance level (Tukey test)

To summarize, it appears probable that the greater strength properties of heartwood compared to sapwood can partially be explained by the heartwood formation process and particularly by the deposition of extractives: this hypothesis needs further specific investigation.

MOE and sMOE showed similar values in the sapwood and heartwood of Marani trees, but lower values in the heartwood than in sapwood in Forestello clones. It can be explained by the lower influence of extractives on them and, on the opposite, by the higher effect of the microfibril angle (Yang and Evans 2003).

Intra- and inter-clone variation

The wood specimens were grouped according to whether they were heartwood or sapwood, because of the significant differences found in the previous analysis (Table 5), and the two groups were explored separately.

The significant differences among clones noticed for most of the wood traits, both for hardwood and sapwood (Table 6), are an indication of a medium–high genetic control over wood properties (Zobel and van Buijtenen 1989; Zobel and Jett 1995). HB was the only trait for which no significant differences among clones were observed. This may be due to a real lack of genetic control over it or, more likely, to

Table 6 *F* value and significance of clone effect (and tree effect when significant at least at 1% level) and its proportion of the total variance (% var) for the wood properties of heartwood and sapwood at each site

Trait	Heartwood		Sapwood	
	F clone (tree)	% var	*F* clone (tree)	% var
Marani				
BD	30.8*** (4.8***)	28	18.2***	39
VS	34.3*** (1.7**)	39	9.6***	23
T/R	18.8***	26	27.2***	47
MOE	33.6*** (4.1***)	43	20.8***	51
sMOE	51.2*** (3.9***)	55	4.7** (2.2***)	16
MOR	19.9*** (2.6***)	36	9.60**	37
MCS	18.2*** (3.6***)	29	27.7***	60
MSS	7.9***	23	5.9***	27
HB	2.3 ns	–	4.6**	23
Forestello				
BD	48.3*** (4.2***)	43	21.6*** (2.5**)	31
VS	9.4*** (2.7***)	13	8.9*** (2.6***)	14
T/R	13.8*** (3.3***)	18	13.0*** (2.3**)	21
MOE	27.5*** (4.2***)	42	79.9***	77
sMOE	5.5***(3.8***)	12	27.6***	52
MOR	8.9***	27	19.8***	44
MCS	14.8***	34	34.7***	56
MSS	2.8*	8	24.6***	52
HB	1.9 ns	–	1.6 ns	–

* Significant at 5% level

** Significant at 1% level

*** Significant at 0.1% level

ns not significant

measurement errors affecting the Brinell hardness test method (Negri et al. 1995). However, the hardness of wood usually is positively correlated to wood density that showed a high clonal effect.

Comparisons with the results of previous works are possible only for species other than wild cherry. The most studied trait to date has surely been wood density: Yanchuk et al. (1984) indicated 0.35 and Pliura et al. (2007) between 0.22 and 0.52 as broad sense heritability for wood density in *Populus*; Nepveu and Velling (1983) reported 0.54 for *Betula*; Nepveu (1984) between 0.37 and 0.58 for different species of *Quercus,* and Monteoliva et al. (2005) 0.65 for *Salix*.

Broad sense heritability values are available also for volumetric shrinkage and shape factor in *Betula* (0.35 and 0.34, respectively) (Nepveu and Velling 1983) and *Quercus* (ranging from 0.22 to 0.29 and 0.14, respectively) (Nepveu 1984).

There are even fewer works in literature on mechanical properties. Two different studies carried out on *Populus* gave opposing results: Mátyás and Peszlen (1997) reported no significant differences among the clone means for the measured strength properties, while Hernández et al. (1998) observed a broad sense heritability of 0.34 for the compliance coefficient (the reciprocal of the MOE) and 0.47 for compression strength. Finally, Botrel et al. (2007) found a significant clone effect both for physical (basic density; radial and tangential shrinkage, but not for volumetric shrinkage) and mechanical properties (MOE in compression and in static bending; compression strength and MOR) in *Eucalyptus*.

The differences among trees within clones, although sometimes significant, were of little importance (Table 6): this means that several samples within a few trees can be measured, rather than one sample from each tree (a far more costly procedure).

Due to the limited number of clones included in the study, the estimation of the variance components has to be read with caution, but some interesting comments and useful general deductions are possible: for most traits, the percentage of variance explained by the clone effect was usually higher for sapwood than for heartwood, showing a greater environmental influence on the heartwood characteristics (Table 6).

Environmental influence on heartwood formation was also suggested by Rink and Phelps (1989) in their report on a black walnut progeny test, as a possible explanation of the greater narrow sense heritability of specific gravity for sapwood (0.54) compared to that for heartwood (0.35). In confirmation of this, further studies reported the lack of genetic control and the strong growth environment influence on ethylene production (Nelson et al. 1981), the amount of which seems to be linked to extractive, and consequently heartwood formation (Hillis 1987; Taylor et al. 2002).

In order to shorten the improvement process, selection is usually carried out on young trees, when the heartwood is not yet formed, even though the heartwood is the final product. Consequently, an investigation of the relationship between heartwood and sapwood properties could reveal important information. Generally, the correlation coefficients between the sapwood and heartwood properties were positive and high (Table 7; Fig. 1). This was not true for the shrinkages and T/R in the Forestello specimens; on the contrary, the highest coefficients were observed for the wood mechanical properties.

Table 7 Pearson correlation coefficient (*r*) between heartwood and sapwood groups, calculated for each trait and site

Trait	Marani *r*	Forestello *r*
BD	0.70***	0.76***
VS	0.50**	0.08 ns
T/R	0.50**	0.39 ns
MOE	0.70***	0.74***
sMOE	0.57***	0.62**
MOR	0.58***	0.61**
MCS	0.69***	0.82***
MSS	0.71***	0.62**

* Significant at $\alpha = 0.05$

** Significant at $\alpha = 0.01$

*** Significant at $\alpha = 0.001$

ns not significant

In contrast to the results of this study, Rink and Phelps (1989) reported a significant but poor phenotypic correlation coefficient (0.28) between heartwood and sapwood specific gravity in walnut, suggesting a clear need for further investigation involving more genotypes and different species, in order to clarify the role that heartwood formation plays in determining the final wood properties and to what extent genetic control affects this process.

However, the *clone* × *cambial age* interaction was always far lower than the clone effect and correlations between sapwood and heartwood values were positive, which means that a quite efficient selection made on the basis of sapwood traits should provide an efficient means of selecting heartwood traits. Early selection based on wood traits (when heartwood is not yet formed) thus would seem possible.

Inter-site variation

The multi-site analysis showed a general significance of site effect and *site* × *clone* interaction, denoting some influence of growth conditions on wood characteristics (Table 8). The clone variance component over the two sites, although always significant, was generally lower than for the individual sites. This can be attributed to the increase in environmental variation when considering more than one location, and the limited set of clones under analysis.

In any case, wood properties were more stable than growth traits across the different environments, in agreement with previous reports, which focused mainly on wood density (Zobel and Jett 1995; Zhang et al. 2003; Pliura et al. 2007).

Finally, the clone effect was generally of greater importance for sapwood than for heartwood properties, confirming what was shown and discussed at the site level. As an example, the percentage of variance explained for BD by the clone factor was, respectively, 7 and 21% for heartwood and sapwood; 26 and 46% for MCS and 9 and 39% for MSS.

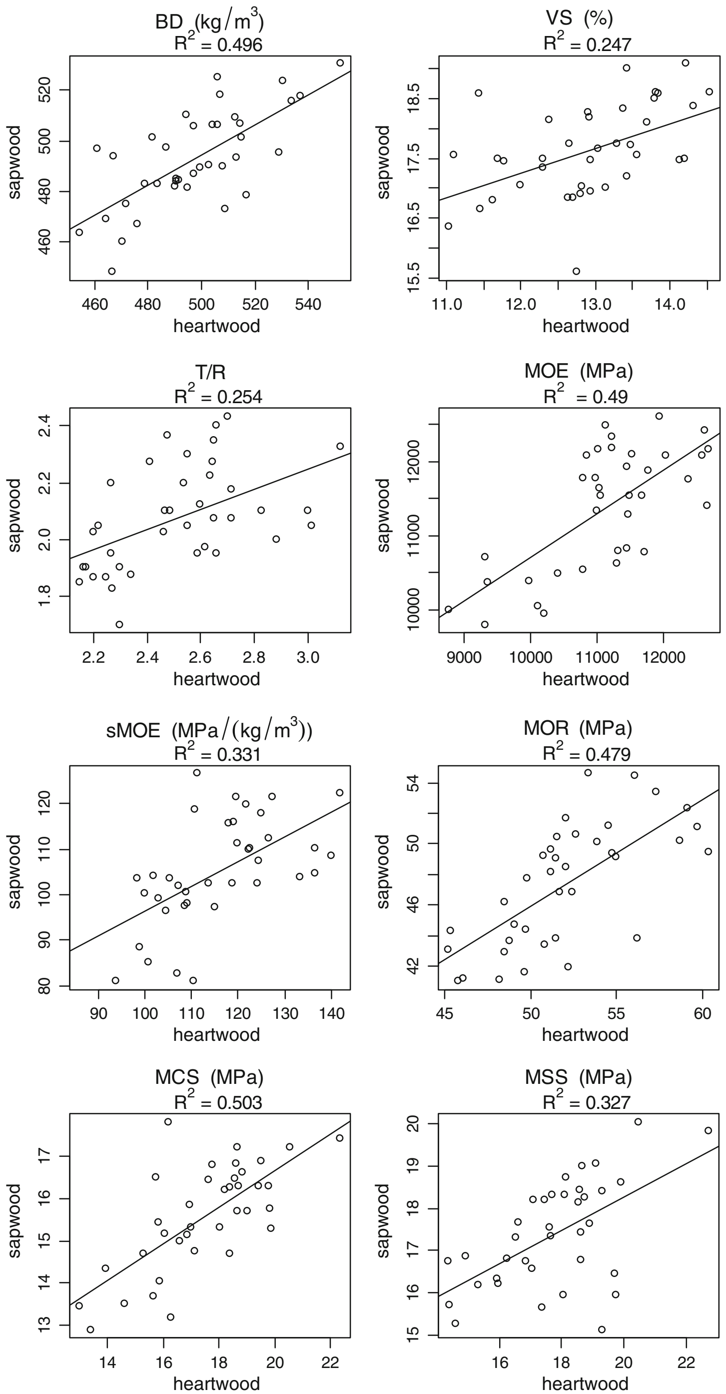

Fig. 1 Relationship between heartwood and sapwood for all the wood traits in the Marani samples

Table 8 *F* values and significance of the main effects (site, clone and interaction) of the site combined analysis for the wood properties of heartwood and sapwood

Trait	Heartwood			Sapwood		
	Site	Clone	Site × clone	Site	Clone	Site × clone
BD	312.9***	11.0***	18.7***	15.1***	18.4***	5.4**
VS	314.8***	7.7***	15.4***	5.3*	5.4**	5.7**
T/R	0.0 ns	4.4**	14.7***	98.7***	5.5**	19.2***
MOE	0.1 ns	49.1***	5.4**	55.2***	67.0***	16.6***
sMOE	58.4***	17.7***	6.42***	72.4***	10.6***	8.9***
MOR	40.2***	7.6***	9.8***	19.6***	11.1***	12.6***
MCS	69.7***	20.3***	6.5***	35.2***	48.4***	11.8***
MSS	11.5***	5.2**	0.7 ns	8.1**	22.9***	0.6 ns
HB	2.7 ns	0.8 ns	1.1 ns	3.8 ns	4.6**	0.3 ns

* Significant at 5% level

** Significant at 1% level

*** Significant at 0.1% level

ns not significant

Conclusion

The enlightening experience gained through wild cherry breeding programmes and the establishment of clonal trials has allowed further investigation into the wood properties of genotypes previously selected on growth and tree architecture basis.

Nearly all the wood traits here studied showed a significant clone effect, confirming the influence of genetic factors on wood properties.

The differences observed between sites emphasize not only the importance of proper site selection, but also, primarily, the need for correct silvicultural practices. The success of plantations aimed at timber production is governed by a combination of three co-factors: genotype, environment and silvicultural practices.

The diversity between heartwood and sapwood properties demonstrates how useful an understanding of within tree wood trait variability is for breeding purposes. But, at the same time, the clear correlation between heartwood and sapwood properties allows early selection based on sapwood properties to improve heartwood too (that is what the wood industry requires).

In the future, further examination of more genotypes will be necessary to determine genetic parameters more accurately.

In this paper, most of the main physical and mechanical properties of wood have been analysed to provide as much information as possible on the genetics of wood. In a second paper, further discussions will be developed to establish those traits that will be useful to concentrate upon for the interest of the breeders.

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Standards

EN 1534	Wood and parquet flooring—Determination of resistance to indentation (Brinell)—Test method
ISO 3131	Wood—Determination of density for physical and mechanical tests
ISO 3133	Wood—Determination of ultimate strength in static bending
ISO 3347	Wood—Determination of ultimate shearing stress parallel to grain
ISO 3787	Wood—Test methods—Determination of ultimate stress in compression parallel to grain. (1976)
ISO 4469	Wood—Determination of radial and tangential shrinkage
ISO 4858	Wood—Determination of volumetric shrinkage

References

Baillères H, Vitrac O, Ramananantoandro T, Rozenberg P (2001) Taking into account the intra-tree variability in breeding programs. In: Proceedings of joint meeting wood, breeding, biotechnology and industrial expectation, Bordeaux, France, 11–14 June 2001, pp 120

Bendtsen BA, Senft J (1986) Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci 18:23–38

Botrel MCG, Silva JRM, Trugilho PF, Rosado SCS, Fernandes BR (2007) Genetic gain in physical and mechanical properties of *Eucalyptus* clones. Sci Forest 76:13–19

Brancheriau L, Baillès H (2002) Natural vibration analysis of clear wooden beams: a theoretical review. Wood Sci Technol 36:347–365

Cilas C, Godin C, Bertrand B, Baillères H (2006) Genetic study on the physical properties of *Coffea Arabica* L. wood. Trees 20:587–592

Curnel Y, Jacques D, Nanson A (2003) First multisite clonal test of wild cherry (*Prunus avium* L.) in Belgium. Silvae Genet 52(2):45–52

Ducci F (2005) Methods of detection and selection of base material (In Italian). In: Ducci F (ed) Monograph on wild cherry (*Prunus avium* L.). CRA – Ist Sper Selv, Arezzo, Italy, pp 33–52

Ducci F, Veracini A (1990) Selecting system of superior phenotype trees in genetic improvement of high quality timber broadleaves (In Italian). Ann Ist Sper Selv, Arezzo, Italy 21:57–79

Ducci F, Veracini A, Tocci A, Canciani L (1990) First results from a preliminary trial of clonal forestry with *Prunus avium* L. (In Italian). Ann Ist Sper Selv, Arezzo, Italy 21:81–107

Ducci F, Germani A, Janin G, Proietti R, Signorini G (2006) Clone selection for wild cherry (*Prunus avium* L.) with special reference to some traits used. In: Bozzano M, Rusanen M, Rotach P, Koskela J (eds) Noble hardwoods network. Report of the sixth (9–11 June 2002, Alter do Chao, Portugal) and seventh meetings (22–24 April 2004, Arezzo Italy). IPGRI, Rome, Italy, pp 53–60

Evans JW, Senft JF, Green DW (2000) Juvenile wood effect in red alder: analysis of physical and mechanical data to delineate juvenile and mature wood zones. For Prod J 50:75–87

Grabner M, Müller U, Gierlinger N, Wimmer R (2005) Effects of the heartwood extractives on mechanical properties of larch. IAWA J 26(2):220–221

Green DW, Winandy JE, Kretschmann DE (1999) Mechanical properties of wood. In: Wood handbook—wood as engineering material. Gen. Tech. Rep. Madison, WI, USDA, Forest Service, Forest Products Laboratory, pp 1–45

Hernández RE, Koubaa A, Beaudoin M, Fortin Y (1998) Selected mechanical properties of fast-growing poplar hybrid clones. Wood Fiber Sci 30(2):138–147

Hillis WE (1987) Heartwood and tree exudates. Springer, Berlin

Kelty M (2006) The role of species mixture in plantation forestry. For Eco Manag 233:195–204

Kobliha J (2002) Wild cherry (*Prunus avium* L.) breeding program aimed at the use of this tree in the Czech forestry. J For Sci 48(5):202–218

Martinsson O (2001) Wild cherry (*Prunus avium* L.) for timber production: consequences for early growth from selection of open-pollinated single-tree progenies in Sweden. Scand J For Res 16:117–126

Mátyás C, Peszlen I (1997) Effect of age on selected wood quality traits of poplar clones. Silvae Genet 46(2–3):64–72

Medzegue MJ, Grelier S, M'Batchi B, Nziengui M, Stokes A (2007) Radial growth and characterization of juvenile and adult wood in plantation grown okumé (*Aucoumea klaineana* Pierre) from Gabon. Ann For Sci 64:815–824

Miller RB (1999) Structure of wood. In: Wood handbook—wood as engineering material. Gen. Tech. Rep. Madison, WI, USDA, Forest Service, Forest Products Laboratory, pp 1–4

Minotta G, Santi I, Ponti F (2000) Comparison among wild cherry clones (*Prunus avium* L.) selected for wood production in the northern Appenines (Italy): growth results after 13 years from planting. (In Italian) Monti e Boschi 6:38–47

Monteoliva S, Senisterra G, Marlats R (2005) Variation of wood density and fiber length in six willow clones (*Salix* spp.). IAWA J 26(2):197–202

Muranty H, Schermann N, Santi F, Dufour J (1998) Genetic parameters estimated from a wild cherry diallel: consequences for breeding. Silvae Genet 47(5–6):249–257

Negri M, Berti S, Borchi S (1995) Hardness tests on wood. State of art and comparison among different methodologies (In Italian). Ann Accad Ital Sci For 44:113–160

Nelson ND (1976) Gross influences on heartwood formation in black walnut and black cherry trees. USDA Forest Service, Research paper

Nelson ND, Rietveld WJ, Isebrands JG (1981) Xylem ethylene production in five black walnut families in the early stages of heartwood formation. For Sci 27(3):537–543

Nepveu G (1984) Heritability of wood density and wood shrinkage in three oak species (*Quercus petraea Quercus robur* and *Quercus rubra*). (In French) Silvae Genet 33(4–5):110–115

Nepveu G, Velling P (1983) Genetic variability of wood quality in *Betula pendula* Roth. (In French) Silvae Genet 32(1–2):37–49

Nocetti M (2008) Genetic improvement of trees for wood production with particular reference to wood traits (In Italian). Forest@ 5:112–120. http://www-sisef.it/forest@/

Pliura A, Zhang SY, MacKay J, Bousquet J (2007) Genotypic variation in wood density and growth traits of poplar hybrids at four clonal trials. For Eco Manag 238:92–106

Raymond A (2002) Genetics of *Eucalyptus* wood properties. Ann For Sci 59:525–531

Rink G (1987) Heartwood color and quantity variation in a young black walnut progeny test. Wood Fiber Sci 19(1):93–100

Rink G, Phelps JE (1989) Variation in heartwood and sapwood properties among 10-year-old black walnut trees. Wood Fiber Sci 21(2):177–182

Rozenberg P, Cahalan C (1997) Spruce and wood quality: genetic aspects (a review). Silvae Genet 46(5):270–279

Rozenberg P, Frank A, Cahalan C (2001) Incorporating wood density in breeding programs for softwoods in Europe: a strategy and associated methods. Silvae Genet 50(1):1–7

Santi F, Muranty H, Dufour J, Paques LE (1998) Genetic parameters and selection in a multisite wild cherry clonal test. Silvae Genet 47(2–3):61–67

Savill PS, Kanowski PJ, Gourlay ID, Jarvis AR (1993) Short note: genetic and intra-tree variation in the number of sapwood rings in *Quercus robur* and *Q. petraea*. Silvae Genet 42(6):371–375

Signorini G (2006) Study on the interclonal variability of wood color in wild cherry (In Italian). PhD Thesis, Università degli Studi di Firenze

Taylor AM, Gartner BL, Morrell JL (2002) Heartwood formation and natural durability—a review. Wood Fiber Sci 34(4):587–611

Woeste KE (2002) Heartwood production in a 35-year-old black walnut progeny test. Can J For Res 32:177–181

Yanchuk AD, Dancik BP, Micko MM (1984) Variation and heritability of wood density and fiber length of trembling Aspen in Alberta, Canada. Silvae Genet 33(1):11–16

Yang JL, Evans R (2003) Prediction of MOE of eucalypt wood from microfibril angle and density. Holz Roh- Werkst 61:449–452

Zhang SY, Jiang H (1998) Variability of selected wood characteristics in 40 half-sib families of black spruce (*Picea mariana*). Wood Sci Technol 32:71–82

Zhang SY, Yu Q, Chauret G, Koubaa A (2003) Selection for both growth and wood properties in hybrid poplar clones. For Sci 49(6):901–908

Zobel BJ, Jett JB (1995) Genetics of wood production. Springer, Berlin

Zobel BJ, Sprague JR (1998) Juvenile wood in forest trees. Springer, Berlin

Zobel BJ, van Buijtenen JP (1989) Wood variation. Its causes and control. Springer, Berlin