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ANALYSIS OF PHYSICAL PROPERTIES OF WOOD IN THREE SPECIES OF GALICIAN OAKS FOR THE MANUFACTURE OF WINE BARRELS

PART I: WOOD INFRADENSITY

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ABSTRACT

The current study about physical properties of wood of *Quercus robur* L., *Q. petraea* (Matt.) Liebl., and *Q. pyrenaica* Willd. in Galicia (northwest of Spain) was based on the determination of proportion of sapwood, heartwood, infradensity, and porosity to understand and estimate the variation of these characteristics and/or properties in the Galician oaks. For this, it was necessary to fell several trees within the study area. In total, 45 trees were chosen in 15 different stands of provinces of Lugo and Ourense, i.e., we have obtained 45 wood slices of *Quercus* at 60 cm tall on the trunk of the tree, and 194 wood samples with a parallelepiped shape and dimensions of 2×2×4 cm ± 1 mm.

The infradensity characterization reveals that oak wood from Galicia has a greater infradensity than French oaks, and *Quercus pyrenaica* has a higher infradensity than *Q. robur* and *Q. petraea*. There is a strong variation of the same based on the geographic origin, but there is almost no variation inside a plot.

The global objective was to realize a detailed description on the physical properties of wood of these species for its possible use in industry cooperage. For this, the objective of this initial work was to begin with the study of wood infradensity.

KEYWORDS: *Quercus robur*, *Q. petraea*, *Q. pyrenaica*, wine barrels, infradensity.

INTRODUCTION

The forest planning and management has a considerable influence on the sustainability of forest ecosystems (Decocq et al. 2004). In the case of deciduous hardwood forests in general and oak forests specifically, applied silvicultural practices are part of the forest tradition (Bouchon and Trencia 1990). The silviculture utilized are well developed and up to date in European countries where these species are of great economic importance, where thousands of hectares of oak forest have been managed for centuries (Bary-Lenger and Nebout 1993; Harmer and Morgan 2007).

However, the situation in the study area is awfully different from that in the above mentioned countries, as there is less knowledge about the management treatments that should be applied to autochthonous broadleaf forests. Galician oaks present a varied range of ages and qualities, as a result of the different uses and their status of conservation (Diaz-Maroto et al. 2005). Coppice forest predominates and it requires continual management otherwise the stands will age and stagnate (Diaz-Maroto et al. 2006a; Van Calster et al. 2007). Many of these forests were intensively exploited (i.e. for the wood and firewood extractions for domestic, and industrial uses for the naval industry), and in many cases inappropriate silvicultural practices have been applied (pollarding and felling of the best trees) (Ruiz de la Torre 1991). Most recently, as a result of rural depopulation, technological developments and social requests, there was a change during the past century from overexploitation of many of them to a total lack of exploitation (Reque and Bravo 2007). The status of these forests has changed recently and there is now a high social demand for its conservation (Collins and Carson 2004). As outlined in Council Directive 92/43/EC, they are habitats of Community interest and should be conserved; remain basic, in many areas of northwest Spain, to implement sustainable rural development.

Oak forests, pure stands or mixed with other deciduous species, occupy an area of 246,445 ha in Galicia, i.e. 18 % of the total forestry area (MAGRAMA 2011). Within the region, these species behave as a robust, light-demanding species, which does not tolerate shade at early stages of development and the seedlings languish quickly undercover. The most important oak stands are found on steep slopes, where they have survived largely because felling would be complicated (Ruiz de la Torre 1991). The oak trees are little used in the forestry industry, the small stands and large the number of owners does not facilitate its industrial development. Forest management of oak forests is virtually nonexistent and the use of oak wood is almost limited for firewood (Diaz-Maroto et al. 2005). This is the main reason why it would be well advised to develop an industry for a better value of these species.

Galicia has, among other areas, a wine growing area called the "*Ribeira Sacra*". The geography and climate of this special site, the landscape, and the quality of the wine that it produces, have created a Protected Designation of Origin (PDO). The wine producers of the Ribeira Sacra are passionate about their region. They abstain to make the aging of wines in French oak barrels or American, because wood aromas aren't produced of Galicia (Alanon et al. 2011a). They use the old French oak barrels in which wood aromas have disappeared a long time, so the wine retains its authentic "*aroma*" of Galicia. But, it has not aromas that make the wine so special. A good solution of this dilemma would be to use oak barrels of Galicia; the wine would keep its local origin and benefit of wood aromas. Therefore, using Galician oaks for making barrels would be a great way to develop a cooperage industry (Alanon et al. 2011b).

The problematic of our work was to study the anatomical and physical features of wood of three species autochthonous oaks of Galicia (*Quercus robur*, *Q. petraea* and *Q. pyrenaica*) for the manufacture of wine barrels. Our global objective was to carry out a full description on the characteristics and/or physical properties of wood of these species for its possible use in industry cooperage as key for sustainable rural development in many areas. For that, the aim of this initial work was to start with the study of wood infradensity.

MATERIAL AND METHODS

Study area

The study area comprises the Autonomous Community of Galicia, located in the NW Spain, with a surface of ~ 3 million ha. The mean altitude is 508 m and slopes of more than 20 % present in half of the territory. The lithological composition is varied, although there is a dominance of siliceous substrates, such as, granite, schist, slates and quartzite; the climate is diverse, but generally classified as Humid Oceanic, with a certain Mediterranean influence in some zones. Annual precipitation varies between 600 to more than 3000 mm, and the average temperature is near to 13°C (Diaz-Maroto et al. 2006a). The climax vegetation is the deciduous hardwood forests characterized by various oak species; summer-green deciduous forests prevail (Buide et al. 1998).

Sampling and data measured

The total area was considered as a single unit, where zones for data collection were selected, taking care to include an adequately representative number of oak stands, on the basis of the data included in the Forest Map of Spain (Ruiz de la Torre 1991). The minimum area of the stands ranged between 0.5 and 1 ha, which avoided problems related with the edge effect (Rondeux and Pauwels 1993). In total, 45 trees were chosen on different 15 stands of the eastern provinces of Galicia, Lugo and Ourense, i.e., we have cut 45 wood slices of *Quercus* at 60 cm tall on the trunk of the tree, and obtained 194 wood samples with a parallelepiped shape and with dimensions of 2×2×4 cm ± 1 mm. We can notice that the accuracy of ± 1 mm isn't really important because we can overcome the inaccuracies of the geometric shape thanks to the water displacement method.

As 69 % of Galicia area is below 600 m above sea level, that is why a lot of stands are located on land with steep slopes. Since as we discussed above, the most important oak stands are found on abrupt slopes, where they have survived largely because felling would be complicated owing to the physiography. This fact is a problem because a strong slope encourages the creation of the tension wood with a heart off centre, which is not appropriate to manufacture barrels (Lehringer et al. 2008).

Tab. 1 shows the summary of the main features of the slices of wood from trees felled in the study area (from normal tree to heart strongly off centre).

Tab. 1: Summary of the main features of the slices of wood from trees felled.

Species	Normal tree	Heart a little off centre	Heart off centre	Heart strongly off centre	Total
Quercus robur	7	4	4	2	17
Quercus petraea	6	--	8	1	15
Quercus pyrenaica	5	2	3	3	13
Total	18	6	15	6	45

Statistical analysis

Bakour (2003) used a short sample of wood to determine the length of the tree parts with measures by a ruler. We propose to work with the software *ImageJ* that is public domain Java image processing program. With *ImageJ* we can calculate the areas of each part of the tree (bark, sapwood and heartwood) and their relative proportion on the wood. The precision of this method will be better that using a short sample. Indeed, the whole sample wood will be used and the singularity of each sample will be considered. *ImageJ* was designed with an open architecture than provides extensibility via Java plugins. It is multithreaded, so time-consuming operations such as image file reading can be done in parallel with others. It can calculate area and pixel value statistics of user-defined choices. Also can measure distances and angles and create density histograms. It supports standard image processing functions such as contrast manipulation, sharpening, smoothing, edge detection and median filtering. Spatial calibration is available to provide real world dimensional measurements in units such millimetres (Ferreira and Rasband 2012).

Description of the method step by step

Getting pictures of samples

The pictures were taken by a Canon EOS 550D. This camera uses a special structure that ensures an optimal light and the distance between the camera and samples is always the same. The precision of the picture is optimal.

Definition of the scale

The first step consists to define the spatial scale of the active image so the measurements results can be presented in calibrated units. Here the centimetre unit will be used. Before using this command, we need to make a line selection that corresponds to a known distance. We have taken our pictures with a ruler to realize easily this step. *ImageJ* will have automatically filled in the distance in pixels based on the length of the line selection (Ferreira and Rasband 2012).

Selections of the areas

The second step consists to use the polygon selection tool to create irregularly shaped selections defined by a series of the line. To create a polygon we need to click repeatedly with the mouse to select line segments that correspond to the border of the various areas. Also, *ImageJ* has an automatic selection tool called *wand toll*. We can used the tolerance of the tool to define the border of the automatically selection. The selection of the bark border is the most difficult. The perimeter is irregular, and sometimes it is difficult to see clearly the limit of the border. The area of the sapwood could be calculated by subtraction of the heartwood. Finally, the area of the bark could be calculated by subtraction of the sapwood.

Infradensity of wood

Wood density varies with tree species, growth conditions and the part of the tree measured. The main stem generally has a higher density that the branches, while fast growth is generally related to relatively low wood density. The knowledge about the "*infradensity of wood*" is useful for estimating the porosity (Pot et al. 2013). Bakour (2003) defines infradensity as the ratio of the wood mass to the volume it occupies:

$$\rho = M_0 / Vs$$

where: M_0 - oven-dry mass of the wood,
Vs - saturated volume.

Infradensity has the units of mass divided by volume such as $g.cm^{-3}$ or $kg.m^{-3}$ (Gelhaye and Guilley 2000).

There are many methods to determine the infradensity of wood and each method have advantages and disadvantages. In these methods, the determination of the oven-dry mass (M_0) is always the same. Oven-dry weight is measured from a wood sample by drying it in a well ventilated oven until it achieves constant weight. This usually takes 24 to 72 hours at 103°C

(Pasztory et al. 2014). Drying depends on the quality of the drier, and if it is necessary we can check the constant weight hypothesis by weighing the samples at regular intervals. Moreover, we can use a desiccators charged with granulated silica to cool the sample. The samples should be weighed one by one immediately after being taken out of the drying oven (Bakour 2003). Mass can be quickly and accurately determined with precision balances.

Getting and measuring the saturated volume (Vs) is more difficult. There are various aspects we need to be conscious to understand the different methods to get the saturated volume. The first difficulty is to be sure that all the empty spaces of the wood are filled with water. The second consists to limit the dispersion in water of soluble substances that could represent up to 4 % of the volume of the sample; also the differences in density and void volume (porosity) may arise simply from differences in the anatomy of the wood modified by the effect of extractives (Polge 1966). The first method involves of realizing the immersion in the water under a lower pressure in order to assure a complete filling of the empty spaces. The second consists of boiling the wood samples during 15 hours. This method is called "*The maximum moisture content's method*" (Keylwerth 1949). Finally, the third method entails an immersion in cold water during 24 hours minimum. With this, we can not assert a lower dispersion of soluble substances, that does not exist in the first and second method. Moreover, if the immersion in cold water is realized under a lower pressure, both of the difficulties are ignored (Vivas 2000). For these reasons, we will use this method in our study.

RESULTS AND DISCUSSION

Results and interpretation of the infradensity

The selection program of the samples follows the criteria following:

- Three species of oak: *Quercus robur*, *Q. petraea*, and *Q. pyrenaica*
- Three types of wood: sapwood, heartwood, and juvenile wood
- Three types of tree: with rotten heart, with an off-center heart, and tree with a normal heart.

Tab. 2 presents the distribution of the wood samples in function of the species and the type of wood.

Tab. 2: Distribution of the samples depending of the species and the type of wood.

Species/ Type of wood	***Quercus robur***	***Quercus petraea***	***Quercus pyrenaica***	**Total**
Sapwood	33	19	29	81
Heartwood	27	27	34	88
Juvenile wood	8	6	11	25
Total	68	52	74	194

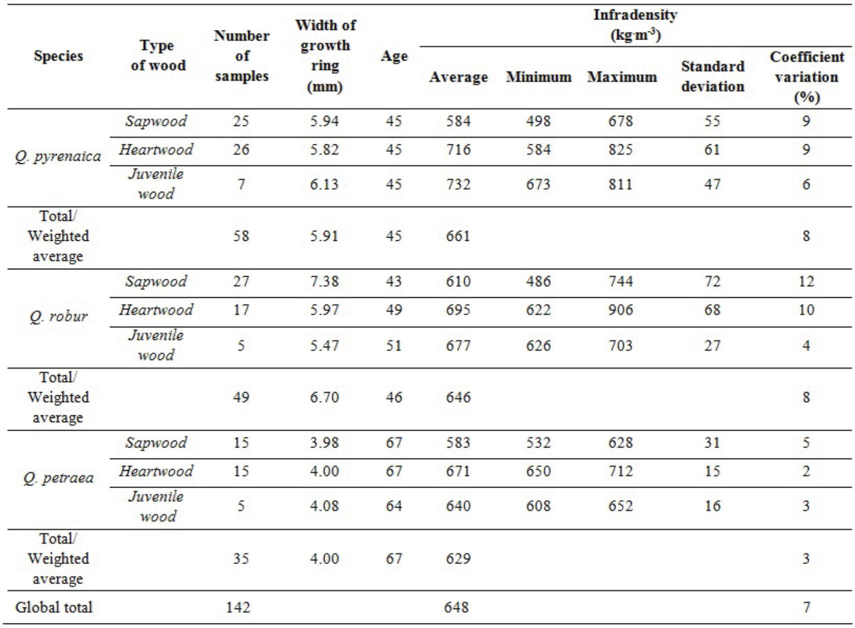
Tab. 3 shows the distribution of the wood samples in function of the species and the type of trees. As we can see, only the slices from *Quercus petraea* present a rotten heart, which is a particularity of the area where these trees were cut.

Tab. 3: Distribution of the samples depending of the species and the type of tree.

Species/ Type of tree	***Quercus robur***	***Quercus petraea***	***Quercus pyrenaica***	**Total**
Tree with rotten heart	0	17	0	17
Tree with an off-center heart	19	0	16	35
Normal tree	49	35	58	142
Total	68	52	74	194

Measures of infradensity of 142 samples of normal oak trees (without a rotten heart or an off-center heart) from 18 different trees and from 3 different species give us an average of 648 kg.m^{-3} with a coefficient of variation (CV) of 7 % and extreme values ranging from 498 to 906 kg.m^{-3} (Tab. 4). The obtained results are superior to data from other studies. Bakour (2003) claims to have found an average of 530 kg.m^{-3} of 588 samples of *Quercus robur* and *Q. petraea* in the French forests. Similarity, Gelhaye and Guilley (2000) found an average of 553 kg.m^{-3} over a set of 90 samples of the same species in the forest of Little Charnie (France). On the contrary, Deret-Varcin (1983) found an average value of infradensity of 450 kg.m^{-3} on a set of 140 samples of *Quercus robur* and *Q. petraea* in the forest of Morimond, France. However, measures of infradensity of Vivas (2000) on a population of samples of *Quercus robur* from the North of Portugal leads of values greater than 650 kg.m^{-3}. It is interesting to note a similarity between our results, average of 648 kg.m^{-3} and the results of Vivas (2000), because we used the same method of measurement in a population of trees relatively close about the geographical

Tab. 4: Values of infradensity, width of growth ring and age in function of the species and the type of wood.



Species	**Type of wood**	**Number of samples**	**Width of growth ring (mm)**	**Age**	**Infradensity (kg·m^{-3})**				
					Average	**Minimum**	**Maximum**	**Standard deviation**	**Coefficient variation (%)**
Q. pyrenaica	*Sapwood*	25	5.94	45	584	498	678	55	9
	Heartwood	26	5.82	45	716	584	825	61	9
	Juvenile wood	7	6.13	45	732	673	811	47	6
Total/ Weighted average		58	5.91	45	661				8
Q. robur	*Sapwood*	27	7.38	43	610	486	744	72	12
	Heartwood	17	5.97	49	695	622	906	68	10
	Juvenile wood	5	5.47	51	677	626	703	27	4
Total/ Weighted average		49	6.70	46	646				8
Q. petraea	*Sapwood*	15	3.98	67	583	532	628	31	5
	Heartwood	15	4.00	67	671	650	712	15	2
	Juvenile wood	5	4.08	64	640	608	652	16	3
Total/ Weighted average		35	4.00	67	629				3
Global total		142			648				7

origin (Lévy et al. 1992; Lebourgeois et al. 2004). The reading of these studies makes it possible to observe the high variability of the oak infradensity according to the geographical origin of samples and probably the method of measurement (Swensson and Toratti 2002).

Infradensity variability in function of the species

Quercus pyrenaica has the highest infradensity of the three species with an average of 661 kg.m^{-3}, followed by *Q. robur* with infradensity of 646 kg.m^{-3}, and finally *Q. petraea* has the lowest with an average of 629 kg.m^{-3} (Tab. 4). These results differ from those usually were obtained in other studies (Deret-Varcin 1983; Bakour 2003), which found higher values for *Q. petraea*. We will try to explain this "*contradiction*".

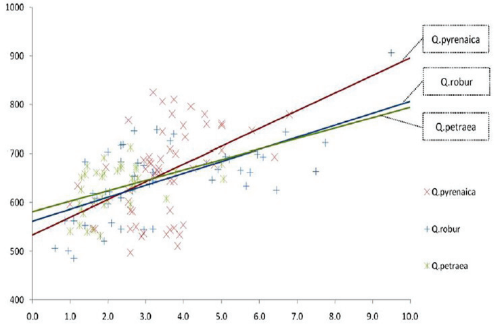
The slices of wood of *Quercus petraea* were obtained of a mountain area with an altitude of 1200 m with steep slopes. Growing conditions are difficult and affect the width of the growth rings: with only 4 mm of average, this species has the lowest average width of growth ring. A lower width in oak species results in a lower texture (Vila-Lameiro and Diaz-Maroto 2005); the proportion of early wood is more important than the late wood (Pasztory et al. 2014).

The wood of oak has an initial porous area; it has many vessels in the early wood (Bary-Lenger and Nebout 1993). Therefore, a lower texture, involves more vessels on the entire surface of the slice, resulting in a lower infradensity than other species (Pot et al. 2013). In addition, the higher average ages of *Quercus petraea* samples have also an influenced in the infradensity. Perhaps we might think that samples of *Q. petraea* are not sufficiently representative, because in Galicia the area occupied by the species is scarce (MAGRAMA 2011).

Quercus pyrenaica has an infradensity higher than *Q. robur* and *Q. petraea* which is in keeping with the study of Fernandez-Parajes et al. (2005).

Infradensity variability of the width of growth rings

Fig. 1 makes it possible to see a positive correlation between the width of growth rings and the infradensity observed. Indeed, a high infradensity corresponds with a maximum of wood material and a small proportion of vessels, in the wood. In the oak species, this small proportion of vessels results in a significant proportion of late wood (where the vessels are smaller), equivalent to a strong texture, almost always involving conditions of rapid growth (Gelhaye and Guilley 2000; Lehringer et al. 2008).



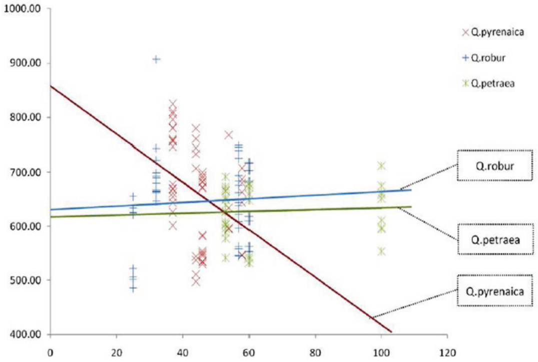
Quercus robur: y = 24.482 x + 561.79; R^2 = 0.3972
Quercus petraea: y = 21.219 x + 581.99; R^2 = 0.1844
Quercus pyrenaica: y = 36.296 x + 533.39; R^2 = 0.2116

Fig. 1: Evolution of infradensity kg.m^{-3} (y-axis) as a function of the width of the growth rings in mm (horizontal axis).

The slope of the modelling of *Quercus pyrenaica* is more important than the modelling of *Q. robur* and *Q. petraea* because of the higher infradensity observed in this species (Fig. 1). The low value of the Pearson correlation coefficient of *Quercus petraea* is partly due to the lack of measurements, only 35 against 58 for *Quercus pyrenaica* (Tab. 4), associated with a large range of ages in the wood slices, causing in *Quercus petraea* a greater dispersion measures.

Infradensity variability in function of the age

We do not even need to look at the Pearson correlation coefficients to find that this model does not work (Fig. 2). We will try explaining why?



Quercus robur: $y = 0.338\ x + 630.96$; $R^2 = 0.0041$
Quercus petraea: $y = 0.166\ x + 617.65$; $R^2 = 0.0048$
Quercus pyrenaica: $y = -4.405\ x + 858.13$; $R^2 = 0.1194$

Fig. 2: Evolution of infradensity $kg.m^{-3}$ *(y-axis) as a function of the age in years (horizontal axis).*

Bakour (2003) showed a negative correlation between age and infradensity for *Quercus robur*. Modelling conducted on 123 experimental trees makes it possible to obtain the equation following:

Infradensity = $600.498 - 0.564 \times \text{age}$; $R^2 = 0.262$

The slope of the function between age and infradensity is only -0.564. However, the slope of the function between the width of growth ring and infradensity is 24.482 for *Quercus robur* (Fig. 1). We can infer that the influence of age in infradensity is less important that the influence of width of growth ring.

Based on this observation, to reveal the influence of age requires a large number of measures and especially an optimum dispersion of the measures on the overall scale of the age (Bakour 2003). As we can see on the Fig. 2, this condition is absolutely not true in our study. That is why we can highlight the influence of the age on the infradensity.

Infradensity variability based on the type of wood

As show in Tab. 4, whatever the species considered, the sapwood has the lowest infradensity with values of 12 to 20 % lower than average infradensity of heartwood and juvenile wood (Deret-Varcin 1983; Gelhaye and Guilley 2000; Lehringer et al. 2008).

It is also interesting to note that the sapwood has the highest coefficient of variation (Tab. 4). Obviously, it is an area with relatively variable infradensity. On the contrary, the heartwood has an infradensity higher than the sapwood, whatever the species (Pot et al. 2013; Pasztory et al. 2014).

On the anatomical point of view, the heartwood contains only dead cells. This central part of tree has undergone chemical, and anatomical sometimes transformations (Hacke and Sperry 2001). The ways of sap flow can be closed (closing bordered pits of conifer tracheids) or become blocked (blocking of broad-leaved vessels trees by membrane expansions called "*tyloses*") (Ghazil 2010).

We can therefore assume that these obstructions leave less space for air and water, thus explaining a higher infradensity than in the sapwood. The sapwood is composed of living cells, the non-obstruction of their vessels is critical to the flow of sap (Azcon-Bieto 2008).

Finally, it is difficult to conclude on the infradensity of the juvenile wood. For the species *Quercus robur* and *Q. petraea*, they have an infradensity slightly lower than heartwood. For *Quercus pyrenaica*, infradensity is slightly higher than in the other species (Tab. 4).

Infradensity variability based on the geographical origin

Many factors influence what we call "*geographical origin*". In our study of sessile oak (Diaz-Maroto et al. 2006b), we reference more than sixty parameters on the geographical origin: climatic, soil and physiographic factors.

In this case, our objective will be study the influence of geographical origin, on the overall, in the infradensity of the Galician oaks.

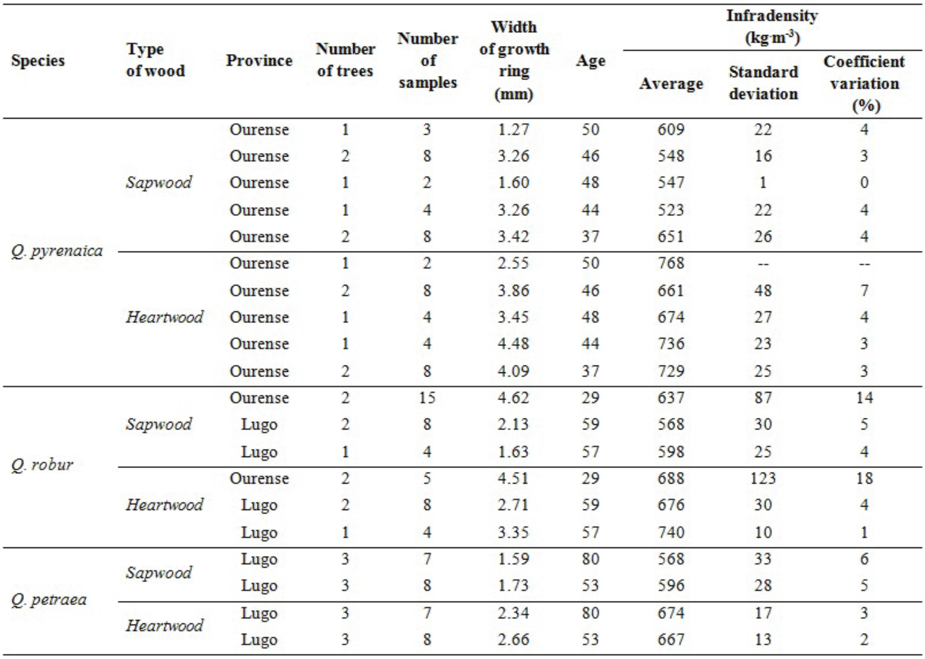
To interpret the results, the data were classified by species and type of wood (sapwood and heartwood), because the differentiation between sapwood and heartwood involves differences in values of infradensity (among 12 and 20 %) that should not be attributed to the factor "*geographical origin*".

On average, as we discussed above, three trees were cut by plot. The important slopes of the study area encourage the presence of off-center hearts. This type of wood is not suitable for the manufacture of barrels (Pot et al. 2013). This is the reason why sometimes there is only one or two trees without off-center heart per plot used for the measurement of infradensity. In each individual tree, different samples were obtained of sapwood and heartwood in function of its proportion in each case (Tab. 5).

It is difficult to identify a tendency because of the small number of measurements. However, data of the Tab. 4 reveal, for similar width of growth rings and ages, the infradensity varies significantly: e.g. there is up to 132 kg.m^{-3} difference for samples of *Quercus pyrenaica*.

Only samples of *Quercus petraea* have values extremely close. This situation can be explained by the geographical proximity of the plots, separated by only a few kilometers, as well as the climatic and physiographic conditions are very similar (Alanon et al. 2011b). Finally, it is interesting to look at the values of the coefficient of variation within the same plot (Tab. 5). On overall, in the same plot, infradensity values have low variation.

Tab. 5: Average values of infradensity, width of growth ring and age based to geographical origin.



Species	Type of wood	Province	Number of trees	Number of samples	Width of growth ring (mm)	Age	Infradensity ($kg \cdot m^{-3}$)		
							Average	Standard deviation	Coefficient variation (%)
Q. pyrenaica	*Sapwood*	Ourense	1	3	1.27	50	609	22	4
		Ourense	2	8	3.26	46	548	16	3
		Ourense	1	2	1.60	48	547	1	0
		Ourense	1	4	3.26	44	523	22	4
		Ourense	2	8	3.42	37	651	26	4
	Heartwood	Ourense	1	2	2.55	50	768	--	--
		Ourense	2	8	3.86	46	661	48	7
		Ourense	1	4	3.45	48	674	27	4
		Ourense	1	4	4.48	44	736	23	3
		Ourense	2	8	4.09	37	729	25	3
Q. robur	*Sapwood*	Ourense	2	15	4.62	29	637	87	14
		Lugo	2	8	2.13	59	568	30	5
		Lugo	1	4	1.63	57	598	25	4
	Heartwood	Ourense	2	5	4.51	29	688	123	18
		Lugo	2	8	2.71	59	676	30	4
		Lugo	1	4	3.35	57	740	10	1
Q. petraea	*Sapwood*	Lugo	3	7	1.59	80	568	33	6
		Lugo	3	8	1.73	53	596	28	5
	Heartwood	Lugo	3	7	2.34	80	674	17	3
		Lugo	3	8	2.66	53	667	13	2

CONCLUSIONS

First, we should mention that the number of data used in our work has not possible to obtain in a reliable for studying variability infradensity depending on the tree age. However, if we have obtained adequate results for the remaining variables related to that characteristic of wood:

- On average, the oak species in Galicia have an infradensity higher than the oaks of other countries with which we compared.
- With a width of growth rings and age similar, *Quercus pyrenaica* has a higher infradensity than *Q. robur* and *Q. petraea*.
- Infradensity increases with the width of growth rings.
- The timber has an infradensity of heartwood, between 12 to 20 %, higher than sapwood.
- There is a large variation of infradensity based on geographical origin.
- The infradensity of trees from the same plots varies slightly.
- The rotten wood has an infradensity lower than normal wood.

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