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ORIGINAL PAPER

Variation of the chemical composition of Pyrenean oak (*Quercus pyrenaica* Willd.) heartwood among different sites and its relationship with the soil chemical characteristics

João Carvalho[1,2] · Óscar Cardoso[1] · Mário Costa[3] · Abel Rodrigues[4]

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Abstract This work presents the results of a study on the variation of the chemical composition of Pyrenean oak (*Quercus pyrenaica* Willd.) heartwood among different sites and its relationship with the soil chemical characteristics. The chemical characteristics of the heartwood are quantified in terms of proximate and ultimate analysis, calorific value and ash composition. Subsequently, the relationship between the wood chemical characteristics and the soil characteristics was also examined. The results showed no significant differences between the wood chemical characteristics from different sites. There are, however, significant differences between trees from the same site regarding the wood ash content, the calorific value and the contents of nitrogen and hydrogen. Strong correlations were observed between the heartwood ash contents of BaO, MnO, CuO and TiO_2 and the soil nitrogen, phosphorous and potassium and the soil exchangeable base contents.

Keywords *Quercus pyrenaica* Willd. · Wood chemical composition · Soil characteristics

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✉ João Carvalho
jpfc@utad.pt

[1] Departament of Forest Science and Lanscape Architecture, Universidade Trás-os-Montes Alto Douro, Vila Real, Portugal

[2] CITAB - Centre for the Research and Technology of Agro-Environment and Biological Sciences, Vila Real, Portugal

[3] IDMEC – Mechanical Engineering Department, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

[4] Instituto Nacional de Investigação Agrária e Veterinária, Av. República, Oeiras, Portugal

Introduction

The study of the wood chemical composition is critical for obtaining pertinent information about its characteristics and to enable better use of wood resources (e.g., Fengel and Wegener 1989; Sjostrom 1993; Rowell 2005). There are no detailed studies in the literature on the chemical characteristics of Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood, and there does not exist any study on the relationship between its chemical composition and the soil chemical characteristics. This is an important issue for the species knowledge (Santos et al. 2012) and for the forest management (Johnson 1993; Sjostrom 1993). Oak forests of these species are very important because of their multiple functions (ecological, economic and social) by the goods and services they provide. The wood from these species may provide a manifold of potential uses, such as flooring, carpentry, veneer, cooperage and energy production (Carvalho 2012; Santos et al. 2012). The sawtimber discards the sapwood for most of these uses because of its low strength and vulnerability to insect attack.

The knowledge of the chemical characteristics of the wood, including its ash composition, may be important for various uses or fields (Hillis 1984; Tsoumis 1991; Quaak et al. 1999; Mandre 2006). For example, the allocation of woody biomass for heating is directly related to its chemical composition in a way that allows evaluating biomass quality for burning by analyzing the wood chips' content of each chemical element (Nordin 1994; Demirbas 2004; Bech et al. 2009; Huang et al. 2009). The chemical composition, determined by the relative proportion and interaction of the different chemical components in their structure (Rowell 2005), is also related to the durability of the wood, color, mechanical strength, hygroscopicity and heating value, among other physical and mechanical characteristics. The ash generated as a by-product of combustion can be used as soil fertilizer (Naylor and Schmidt 1986; Demeyer et al. 2001; Pitman 2006). Application of ash on the ground for recycling nutrients such as potassium, calcium, magnesium and phosphorus can be made for amendment or balancing of the nutrients of agricultural and forest soils (Naylor and Schmidt 1986; Campbell 1990; Steenari et al. 1999; Reijnders 2005).

According to several authors (e.g., Pettersen 1984; Shmulsky and Jones 2011), it is also interesting to know the variability of the wood chemical characteristics that can be attributed to factors such as the species, genetic characteristics and environmental conditions of the tree growth. The study of the wood chemical composition and its relationship with the soil characteristics is also relevant to evaluate the nutrient recycling in the forest (Ranger and Bonneau 1984; Khanna and Fabiao 2002). Information about the quantity of nutrient exports resulting from logging and the availability of nutrients in the forest soils is essential topics in sustainable forestry (Nykvist 1976; Olsson et al. 1996; Brandtberg and Olsson 2012). Moreover, the intensity of forest biomass exploitation for some species affects the soil fertility and its relationship with the nutrients available in the soil (Watmough 2014).

The aim of the present work is to evaluate the variation of the chemical composition of Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood among different sites and its relationship with the soil chemical characteristics.

Materials and methods

The wood chips used in this study were obtained from Pyrenean-oak stands from the north of Portugal, in four different sites, having two different types of parent material (schist and granite) and soil type (Table 1). The sites present a mean annual precipitation ranging from 1080 to 1290 mm and a mean annual temperature ranging from 9.7 to 11.0 °C. The vegetation was a pure stand dominated by Pyrenean-oak with the minor presence of other tree species, namely common cherry (*Prunus avium* L.), madrone (*Arbutus unedo* L.) and Plymouth pear (*Pyrus cordata* Desv.). In each site, a plot of 500 m^2 with homogeneous size classes was established and two dominant trees were selected and harvested for the present study based on the homogeneity of the stand and the indications of Tennent and Burkhart (1981). For the purposes of this study, all the chemical analyses were carried out using heartwood. From each tree and logs, the central board was sawed. Wood slats of the heartwood were obtained with approximately 1 cm thickness, which were subsequently cut into cubes of approximately 1-cm edges and then ground in a mill for chemical analysis. At each site, a soil profile was dug and the horizons, properties and materials were observed for a preliminary soil classification. The final classification was made after the analytical evaluation of the physical and chemical characteristics of the soil (Van Reeuwijk 2002) from the Laboratory of Soil. The classification of the soil type was based on the FAO classification system (FAO 2015). Soil types and textures in Table 1 are the most common found in Pyrenean-oak forests (Carvalho and Parresol 2004; Carvalho 2012). At each site, a composite soil sample was obtained from each horizon and stored in plastic bags. Soil sampling was made at all soil profiles and depths. The chemical parameters analyzed were the following: soil reaction (pH(H_2O)), organic matter (OM), nitrogen (N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O), calcium (Ca), magnesium (Mg) potassium (K), sodium (Na), the sum of exchangeable bases (SEB), exchangeable acidity (AE) and the degree of base saturation (DBS) (Table 2). The soil composition was different at the four sites, mainly in extractable and exchangeable cationic bases, with the Macedo site showing higher amounts of these elements.

The chemical characteristics of the heartwood were evaluated in terms of proximate analysis, ultimate analysis, calorific value and composition of the ashes. The proximate and ultimate analysis and the calorific values of the heartwood were carried out following the procedures specified in the standards ASTM-E-870, EN 14918 and EN 14775, and the chemical composition of the heartwood ash was determined using X-ray fluorescence spectroscopy.

The heartwood and soil chemical parameters were analyzed to determine whether there were significant

Table 1 Physical characteristics of the studied sites

Site	Location lat., long.	Stand age (years)	Parent material	Soil type	Soil depth (cm)	Soil texture
1-Macedo	41°37′N, 6°58′W	53	Schist	*Cambisol* (CM)	95	Silty loam
2-Bragança	41°51′N, 6°46′W	52	Schist	*Luvisol* (LV)	150	Loam
3-Chaves	41°45′N, 7°18′W	52	Granite	*Cambisol* (CM)	140	Sandy loam
4-V.P. Aguiar	41°27′N, 7°40′W	55	Granite	*Leptosol* (LP)	45	Sandy

Table 2 Chemical analysis of the soils

Site	Macedo	Bragança	Chaves	V.P. Aguiar
pH (H_2O)	5.5	5.0	4.9	4.9
OM (%)	1.5	0.4	7.4	4.1
N (%)	0.095	0.032	0.750	0.197
P_2O_5 (mg g^{-1})	8.2	3.9	11.7	6.0
K_2O (mg g^{-1})	189	84	65	108
Ca (mg g^{-1})	2.72	0.45	0.47	1.18
Mg (mg g^{-1})	2.40	0.60	0.07	0.68
K (mg g^{-1})	0.27	0.13	0.08	0.21
Na (mg g^{-1})	0.29	0.10	0.11	0.08
SEB (mg g^{-1})	5.68	1.28	0.73	2.15
AE	0.88	2.97	2.19	1.42
DBS (%)	84.1	34.9	25.7	60.2

variations between trees within the same site and different sites (intra- and interpopulation variation). An analysis of variance was performed for the heartwood elements in order to examine the significance of variance from trees and sites. Further analysis was undertaken to evaluate the relationship between the heartwood and the soil chemical compositions from different sites. A principal component analysis (PCA) with standardized data allowed for an enhanced understanding of the data structure, the interactions between variables and a better interpretation of the results. The correlation matrix was analyzed with the aid of the Bartlett test of sphericity (Gauch 1982; Jolliffe 2002) in order to evaluate the occurrence of significant correlations among the variables. A correlation analysis between the heartwood and the soil chemical elements was performed through the Pearson correlation coefficient (Steel and Torrie 1997; Norman and Streiner 2007).

Results

Table 3 shows the results of the proximate and ultimate analysis, calorific value and ash composition for each sample. The moisture and volatile matter contents are very similar among the samples, but both the ash and the fixed carbon contents show high variability. The average values of the moisture, volatile content, ash and fixed carbon are 11, 86, 0.2 and 3 wt%, respectively, while the average values of the LCV (lower calorific value) and HCV (higher calorific value) are 16.79 and 18.14 MJ kg^{-1}, respectively. The ultimate analysis shows average values of 49 wt% for C, 44 wt% for O, 0.05 wt% for N, 6 wt% for H and 0.01 wt% for S.

As for the composition of the heartwood ash, the most common oxides are CaO with 37 wt%, K_2O with 31 wt%, SO_3 with 11 wt%, MgO and P_2O_5 both with 4 wt% and Al_2O_3 with 2 wt%. The remaining oxides in the heartwood ash present contents lower than 2 wt% (Table 3).

The analysis of variance showed no significant differences between sites in the amounts of the chemical elements of the heartwood, but significant differences between trees in the same site were observed for some variables, namely for the ash content, both for the LCV and the HCV, and for the contents of N and H (Table 4).

In the case of the ash composition, the analysis of the variance did not reveal significant differences between sites and trees in the same site (Table 5).

The PCA for the heartwood chemical characteristics showed that the first four components explained 89.4% of the observed variance and the first two components 57.5%. Figure 1 shows components 1 and 2 from the PCA for the chemical variables of the Pyrenean-oak heartwood. The first principal component correlates positively with LCV, HCV, H, Al_2O_3, BaO, CaO, Cr_2O_3, Na_2O, SiO_2 and SrO. The second principal component shows positive correlations with N, CuO, Fe_2O_3, TiO_2, ZnO and SO_3. The third principal component relates positively with BaO, MnO and Rb_2O.

Figure 2 shows components 1 and 2 from the PCA for the chemical variables of the soil and of the Pyrenean-oak heartwood, which explains 84.1% of the total variance. The first principal component relates positively with some heartwood ash elements such as BaO, MnO, TiO_2, ZnO, SO_2, Fe_2O_3 and CuO, and with the soil OM and N. This component relates negatively with most of the soil chemical characteristics (K_2O, Ca, Mg, K, Ca, SEB, DBS, pH). The second component correlates positively with LCV, HCV and O.

Table 6 shows the significant correlations between the chemical variables of the soil and of the Pyrenean-oak heartwood.

Several soil chemical characteristics (K_2O, Ca, Mg, K, SEB, EA, DBS and pH) present significant negative correlations with the heartwood ash contents of BaO and MnO. The soil N correlates positively with CuO and TiO_2, and the soil P_2O_5 with CuO.

Discussion

The results showed that for a large number of heartwood chemical parameters there are no significant differences between sites. Despite the differences between soils, with the exchangeable bases of the soil of site 1 (Macedo) being higher than those of the other sites, the heartwood chemical composition is similar for all sites. For some elements, however, there are significant differences between trees located in the same site, namely regarding the ash content, both the LCV and the HCV and both the N and the H contents. This significant variation in the heartwood

Table 3 Chemical analysis of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood samples from the various sites

Site sample	1-1	1-2	2-1	2-2	3-1	3-2	4-1	4-2	Mean	CV (%)
Proximate analysis (wt%)										
Moisture	9.7	10.9	11..5	11.7	10.2	10.8	11.4	10.8	10.88	6.2
Ash	0.2	0.1	0.4	0.2	0.2	0.1	0.4	0.2	0.23	51.8
Volatile matter	85.3	84.8	86	86	85.3	87	86.2	83.4	85.50	1.3
Fixed carbon	4.8	4.2	2.1	2.1	4.3	2.1	2.0	5.6	3.40	43.5
Total	100	100	100	100	100	100	100	100		
LCV (MJ kg^{-1})	16.70	18.30	15.20	18.10	16.70	17.80	14.70	16.80	16.79	7.8
HCV (MJ kg^{-1})	18.00	19.70	16.50	19.40	18.10	19.20	16.00	18.20	18.14	7.3
Ultimate analysis (wt%, dry basis)										
Carbon (C)	45.9	49.1	53.2	48.9	46.6	49.2	52.8	49.8	49.44	5.2
Oxygen (dif.) (O)	47.69	44.37	40.05	44.49	46.90	44.26	40.45	43.52	43.96	5.9
Nitrogen (N)	0.1	0.02	0.04	0.005	0.1	0.005	0.08	0.03	0.05	84.6
Hydrogen (H)	6.1	6.4	6.29	6.4	6.19	6.43	6.25	6.43	6.31	2.0
Sulfur (S)	0.011	0.01	0.02	0.01	0.012	0.01	0.02	0.02	0.01	34.8
Ash	0.2	0.1	0.4	0.2	0.2	0.1	0.4	0.2	0.23	51.8
Total	100	100	100	100	100	100	100	100		
C/N	459	2455	1330	9780	466	9840	660	1660	3331	121.7
C/H	7.52	7.67	8.46	7.64	7.53	7.65	8.45	7.74	7.83	5.0
Composition of ash (wt%, dry basis)										
Al_2O_3	0.21	2.85	0.22	1.30	0.48	7.12	0.44	3.72	2.04	119.2
BaO	0.22	0.64	0.56	0.85	1.10	0.80	0.36	0.76	0.66	42.5
CaO	24.80	48.10	20.70	44.40	36.70	34.70	32.2	55.40	37.13	31.5
Cl	0.03	0.12	0.72	0.29	0.15	0.11	0.58	0.07	0.26	99.2
Cr_2O_3	0.001	0.02	0.02	0.02	0.001	0.07	0.008	0.04	0.02	99.3
CuO	0.09	0.12	0.07	0.12	0.44	0.23	0.04	0.11	0.15	84.9
Fe_2O_3	0.12	0.76	0.17	0.22	7.10	1.20	0.2	0.27	1.25	190.7
K_2O	28.60	26.40	60.20	32.40	26.90	21.00	51.3	5.19	31.50	54.7
MgO	1.60	4.46	4.72	5.05	0.87	3.67	3.66	10.50	4.32	67.3
MnO	0.04	0.20	1.25	3.11	3.10	2.66	0.33	0.71	1.43	93.0
Na_2O	0.22	2.20	0.86	0.72	0.99	3.50	0.75	1.40	1.33	79.1
NiO	0.02	0.04	0.04	0.02	0.01	0.01	0.007	0.05	0.02	64.7
P_2O_5	0.94	3.42	5.19	2.30	2.20	4.51	3.65	13.20	4.43	85.7
Rb_2O	0.05	0.04	0.11	0.09	0.13	0.05	0.2	0.01	0.09	71.6
SiO_2	1.80	4.48	1.00	2.41	2.60	12.00	1.68	2.80	3.60	98.6
SO_3	40.90	5.57	2.63	6.28	16.20	7.83	3.09	5.14	10.96	117.0
SrO	0.22	0.38	0.26	0.38	0.59	0.41	0.32	0.55	0.39	33.2
TiO_2	0.04	0.09	0.10	0.03	0.33	0.20	0.15	0.03	0.12	84.5
ZnO	0.01	0.01	0.02	0.01	0.09	0.03	0.04	0.04	0.03	84.3
Total	100	100	100	100	100	100	100	100		

wt weight, *LCV* lower calorific value, *HCV* higher calorific value, *C/N* carbon/nitrogen ratio, *C/H* carbon/hydrogen ratio, Al_2O_3 aluminum oxide, *BaO* barium oxide, *CaO* calcium oxide, *Cl* chlorine, Cr_2O_3, chromium oxide, *CuO* copper oxide II, Fe_2O_3 iron oxide III, K_2O potassium oxide, *MgO* magnesium oxide, *MnO* manganese oxide, Na_2O sodium oxide, *NiO* nickel oxide II, P_2O_5 phosphorus pentoxide, Rb_2O rubidium oxide, SiO_2 silica oxide, SO_3 sulfur trioxide, *SrO* strontium oxide, TiO_2 titanium oxide IV, *ZnO* zinc oxide, *C.V.* coefficient of variation

chemical characteristics between trees in the same site makes the overall variation between sites insignificant. The differences between trees may be attributed to genetic characteristics. Indeed, Zhang et al. (2015) showed that for *Populus tomentosa* Carr. the wood chemical properties were under stronger genetic control than growth traits.

The proximate analysis of the Pyrenean-oak heartwood indicates an ash content of 0.23 ± 0.12 wt%, which is

Table 4 Analysis of variance of the proximate and ultimate analysis of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood samples (significance level of 0.05)

Source of variance	Ash	C	LCV	HCV	C	O	N	H	S	C/N	C/H
Site											
F	9.0	0.689	4.112	4.308	1.110	1.175	1.533	1.151	3.709	1.180	1.134
Sig.	0.052	0.617	0.138	0.131	0.467	0.449	0.367	0.455	0.155	0.447	0.460
Tree											
F	27.0	0.027	25.158	26.785	0.038	0.038	22.533	25.996	2.020	5.817	1.458
Sig.	0.014*	0.881	0.015*	0.014*	0.857	0.857	0.018*	0.015*	0.250	0.095	0.314

Table 5 Analysis of variance of the ash composition of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood samples (significance level of 0.05)

Source of variance	Al_2O_3	BaO	CaO	Cl	Cr_2O_3	CuO	Fe_2O_3	K_2O	MgO
Site									
F	1.214	1.720	0.562	1.783	0.485	3.485	1.568	0.963	2.537
Sig.	0.439	0.333	0.676	0.323	0.716	0.166	0.360	0.512	0.232
Tree									
F	8.471	1.420	7.207	2.315	4.835	0.052	0.694	4.012	5.673
Sig.	0.062	0.319	0.075	0.226	0.115	0.834	0.466	0.139	0.097

Source of variance	MnO	Na_2O	NiO	P_2O_5	Rb_2O	SiO_2	SO_3	SrO	TiO_2	ZnO
Site										
F	7.278	1.095	0.356	1.157	0.381	1.703	0.989	1.068	5.402	1.970
Sig.	0.069	0.471	0.791	0.454	0.775	0.336	0.504	0.479	0.100	0.296
Tree										
F	1.008	4.249	0.533	1.256	3.117	3.524	1.111	0.778	2.545	1.308
Sig.	0.389	0.131	0.518	0.344	0.176	0.157	0.369	0.443	0.209	0.336

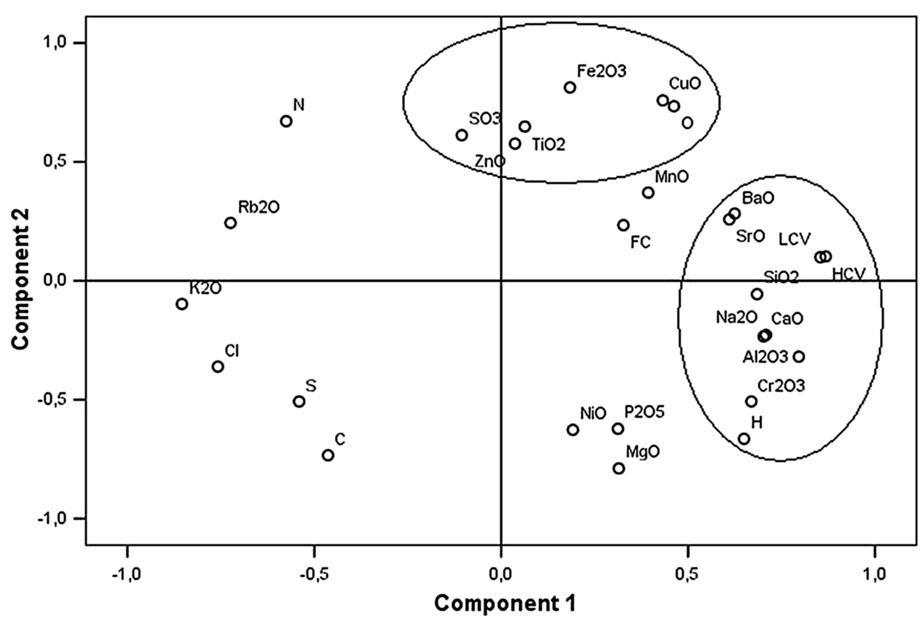

Fig. 1 Components 1 and 2 from the principal component analysis (PCA) for the chemical variables of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood

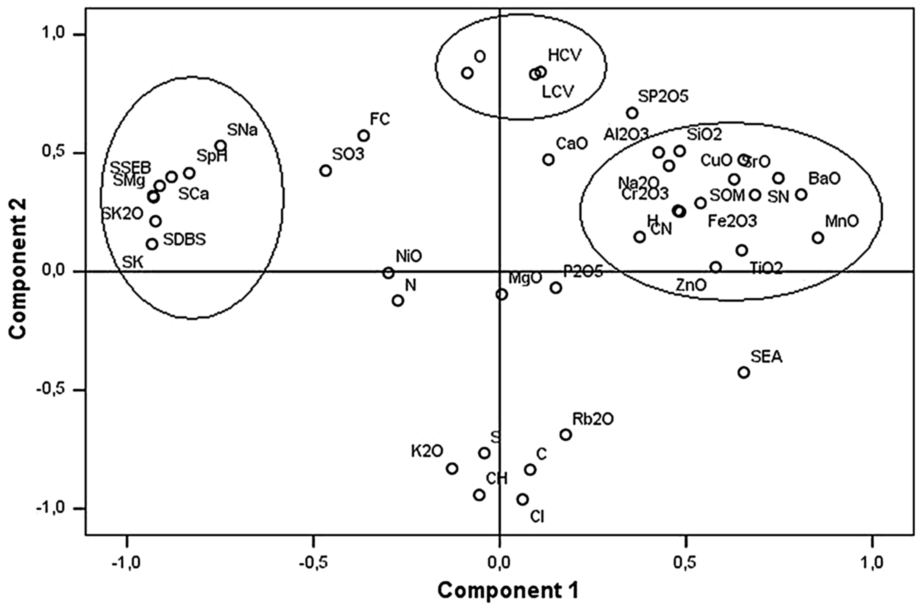

Fig. 2 Components 1 and 2 from the principal component analysis (PCA) for the chemical variables of the soil and of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood (*SOM* soil OM, *SN* soil N, *SP2O5* soil P_2O_5, *SK2O* soil K_2O, *SCa* soil Ca, *SMg* soil Mg, *SK* soil K, *SNa* soil Na, *SSEB* soil SEB, *SEA* soil EA, *SDBS* soil DBS, *SpH* soil pH)

Table 6 Correlations between the chemical variables of the soil and of the Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood (between parentheses are the Pearson correlation coefficient, * significance level of 0.05 and ** significance level of 0.01)

Soil chemical characteristic	Wood chemical elements	
N	CuO (0.842**)	TiO_2 (0.859**)
P_2O_5	CuO (0.760*)	
K_2O	BaO (−0.648*)	MnO (−0.794*)
Ca	BaO (−0.611*)	MnO (−0.784*)
Mg	BaO (−0.626*)	MnO (−0.734*)
K	BaO (−0.716*)	MnO (−0.905**)
SEB	BaO (−0.624*)	MnO (−0.766*)
EA	FC (−0.633*)	MnO (−0.764*)
DBS	BaO (−0.692*)	MnO (−0.888**)
pH	MnO (−0.697*)	

close to the value reported by Jin et al. (2013) for the *Quercus rubra* heartwood (0.13 ± 0.01 wt%). The ultimate analysis data of the Pyrenean-oak heartwood present values in line with those reported in the literature for other species, except for the N content, which presents a mean value of 0.05 wt% that is lower than the values available for others species (0.1–1 wt%).

The major elements present in the heartwood ash in decreasing order are CaO, K_2O, SO_3, P_2O_5, MgO, SiO_2, Al_2O_3, MnO, Na_2O and Fe_2O_3. The other elements are present in quantities smaller than 1 wt%. According to Ljung and Nordin (1997) and James et al. (2012), a large number of minerals present in the ash are mixtures of oxides, hydroxides, silicates, carbonates, among other forms. The properties of the heartwood ash depend on several factors, including the type and source of wood, soil type and climate and storing conditions (e.g., Naik and Kraus 2003; Koppejan and Loo 2008; Serafimova et al. 2011).

The heartwood chemical characteristics, including the ash composition, present a number of positive correlations between them, namely the following correlations: C–S, C–Cl, C–K_2O, O–SO_3, H–Al_2O_3, H–CaO, H–Cr_2O_3, H–MgO, S–Cl and S–P_2O_5.

The contents of BaO, MnO, CuO and TiO_2 present in the heartwood are highly related to some soil chemical characteristics. These elements are important micronutrients involved in different biochemical processes (Marschner 1986; Pais et al. 1998; Hruby et al. 2002; Broadley et al. 2012; Lambers et al. 2015). Manganese is an essential micronutrient for plant growth and development, being involved in multiple processes; it plays an important role in enzyme activation, biological redox processes of various metabolic pathways associated with photosynthesis, respiration and synthesis of proteins, carbohydrates and other components (McHargue 1922; Liverness and Smith 1982; Chatzistathis and Therios 2013). Titanium plays a role in plant development (Pais 1983), by stimulating the activity of some enzymes and uptake of nutrients (Dumon and Ernst 1988; Hruby et al. 2002). Some of these elements, particularly the heavy metals, also play a relevant role against microorganisms and wood decay (Ostrofsky et al. 1997; Sawai 2003; Arantes and Goodell 2014).

Several studies have shown that the absorption of micronutrients is influenced by the soil pH (e.g., Augustin et al. 2005; Broadley et al. 2012). The bioavailability of soil Mn increases with decreasing soil pH and exchangeable bases (Kogelmann and Sharpe 1999; Lambers et al. 2015). Watmough (2014) has also found an inverse correlation between Ba wood concentration and soil bases. The wood elements' concentration can also be used to evaluate or monitor changes in soil and environment quality (Guyette and Cutter 1994; Poszwa et al. 2003; Augustin et al. 2005). For example, the Mn concentration in plants has been used as a biomarker for the switch of buffering mainly with the exchange of base cations and the dissolution of aluminum oxides (Hildebrand 1986; Ulrich 1991). Soil type and chemical characteristics should be taken into account too when designing a dendrogeochemical study of environmental change.

The average content of Mn found in the present study is 2583 µg g^{-1} DW, which is relatively high. Yang et al. (2015) reported Mn concentrations ranging from 300 to 800 µg g^{-1} for *Salix* clones, while in Mn-contaminated soils the concentrations varied between 1840 and 4572 µg g^{-1}. *Pseudotsuga menziesii* showed maximum Mn concentrations of 3260 µg g^{-1} DW (stem) (Dučić et al. 2006), while in this study the maximum concentration was 5557 µg g^{-1}. Augustin et al. (2005) reported concentrations ranging from 50 to 100 µg g^{-1} for Norway spruces, while in contaminated soils varied between 400 and 600 µg g^{-1}. The Mn concentrations in the present Pyrenean-oak wood are also higher than those found in the wood from *Cassia siamea* (Cassia), *Azadirachta indica* (Neem) and *Holoptelia integrifolia* (Holoptelia) growing in contaminated soils (wood concentrations of Mn ranging from 626 to 1248 µg g^{-1}) (Raju et al. 2008).

Conclusion

A study on the variation of the chemical composition of Pyrenean-oak (*Quercus pyrenaica* Willd.) heartwood among different sites and its relationship with the soil chemical characteristics is presented. The chemical characteristics of the wood were quantified in terms of proximate and ultimate analysis, calorific value and ash composition. Subsequently, the relationship between the wood chemical characteristics and the soil characteristics was also examined. The main conclusions from this study are as follows:

- We found no significant differences between the heartwood chemical characteristics from different sites.
- Significant differences between trees from the same site regarding the wood ash content, the calorific value and the contents of nitrogen and hydrogen were observed.
- Strong correlations were observed between the heartwood ash contents of BaO, MnO, CuO and TiO_2 and the soil nitrogen, phosphorous and potassium and the soil exchangeable base contents.

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