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Effect of site conditions on the properties of hawthorn (*Crataegus azarolus* L.) wood

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Abstract: This study investigated the influence of site conditions on the physical and morphological properties of hawthorn (*Crataegus azarolus* L.) wood grown in Zagros forests of Iran. Hawthorn is a valuable woody species in Iran's Zagros forests with data deficiency in its wood properties. To our best knowledge, there is no study on the properties of hawthorn wood. Twenty-seven mature trees were randomly chosen and sampled at three altitude levels (1 800–2 000, 2 000–2 200, and 2 200–2 400 m) in the Bazoft region of Chaharmahal Va Bakhtiari, Iran. Dry wood density, volumetric shrinkage, fibre length, fibre diameter, cell wall thickness were then determined. Multivariate analysis of variance (MANOVA) was conducted to evaluate significant differences between the mean values of studied wood properties at different altitude levels and slope classes. Moreover, the relationships between the above-mentioned properties and some site conditions (temperature, precipitation, altitude, and slope) as well as growth parameters of trees (tree height, DBH, age, crown dimensions, volume, etc.) were studied by principal component analysis (PCA). The results indicated that trees growing at the second altitude level had the highest oven-dry density values, and those at the third altitude level had the lowest ones. Results also indicated a significant effect of altitude levels on fibre length, fibre diameter, and cell wall thickness. In contrast, a significant difference was found between the mean values of fibre diameter at different slope classes. PCA indicated that altitude, precipitation, and temperature are the most important environmental site variables affecting the wood characteristics.

Keywords: altitude; fibre dimension; Zagros forests; oven-dry density; PCA

In Iran, forests cover about 12 million ha (Haidari et al. 2013). Zagros forests cover about 5 million hectares, representing 40% of Iran's forests (Sagheb-Taleb et al. 2004). The climate in Zagros is mainly affected by westerly disturbances and the Azores high during the cold (November–March) and warm (May–September) season, respectively, resulting in a clear distinction between a wet winter and a dry summer (Azizi et al. 2013). The main hardwood species in this area are *Quercus* spp. (oaks), *Pistacia mutica* (wild pistachio), *Crataegus* spp. (hawthorn) and *Pyrus* spp. (pear) (Jazirehi, Rostaghi 2003). *Crataegus* spp. belong to the family Rosaceae and subfamily Maloideae including about 300 species which are grown in Europe, North Africa, West

Asia, and North America. *Crataegus* species are shrubs or small trees, mostly growing up to 15 m (Phipps 1997).

It has been indicated that the combination of environmental and climatic factors affects tree growth and wood properties (Zobel, van Buijtenen 1989). Geographic factors (latitude, altitude, aspect and slope), climatic factors (temperature and humidity), biotic factors (humans, animals, plants and microorganisms) as well as soil properties can influence wood characteristics (Usta et al. 2014; Kaygin et al. 2016; Topaloglu et al. 2016; Nazari et al. 2020). Studies on the relationship between wood properties and ecological factors are of great importance in understanding wood applications as well as cre-

ate a database for different wood species. Besides, as the climate is changing very fast, these studies can be used for modelling of the wood properties in the future. Studies such as Noshiro et al. (1995), Alves and Angyalosy-Alfonso (2000), Bosio et al. (2010), Kiaei et al. (2019) stated that there are significant associations between anatomical wood characteristics and ecological factors.

Numerous studies aimed to understand the relationship between physical wood properties and elevation gradient. Govorcin et al. (2003) pointed out that wood density of *Fagus sylvatica* declined with increasing elevation. On the other hand, Kiaei (2012) reported that wood density of *Carpinus betulus* increased with increasing elevation. Even more, Kiaei (2012) reported that volumetric shrinkage of *C. betulus* wood increased with increasing elevation. However, it was reported that there was no significant effect of elevation on the wood density of *Alnus acuminata* (Hernandez, Restrepo 1995).

Many studies have determined the association between the anatomical structure and environmental features, as was indicated by Noshiro et al. (1994) for *Alnus nepalensis*, by Yilmaz et al. (2008) for *Quercus pontica*, by Topaloglu et al. (2016) for *Fagus orientalis*. It was reported that there was no association between the anatomical structure of wood and elevation for *Dodonaea viscosa* by Liu and Noshiro (2003) and for *Buddleja cordata* by Aguilar-Rodriguez et al. (2006). Topaloglu et al. (2016) reported that *F. orientalis* trees growing at an elevation of 800–1 000 and 0–200 m differed significantly in vessel and fibre length, respectively. Considering the importance of ecological factors for the wood properties and valuable position of hawthorn (*Crataegus azarolus* L.) wood grown in Zagros forests of Iran, the present study aimed to investigate the variation of oven-dry density, volumetric shrinkage, fibre length, fibre diameter, and the cell wall thickness of hawthorn wood depending on different elevation gradient and slope classes as well as to explore the association between wood properties and environmental factors.

MATERIAL AND METHODS

Study area and sampling. This study was conducted on trees collected from 27 sample plots from nine ecosite groups [three forest sample stands along an altitudinal gradient (below 1 800, 2 000–2 200 and above 2 400 m a.s.l.) × three terrain slope classes

(less than 30%, 30 to 45% and more than 45%)] in the hawthorn forests creating three replicates in each ecosite in the Bazoft region forest of Chaharmahal Va Bakhtiari (Iran) (Figure 1 and Table 1). In each ecosite, three plots were established, accordingly 27 plots were selected in the study area. In total, 27 healthy trees (3 trees × 3 altitudes × 3 slopes) were selected (one tree in each plot). The main dimensions of the tree and site properties are presented in Table 1. The study area is located between 49°59'43"N and 50°15'28"N and between 32°07'42"E and 32°22'25"E in the Bazoft region of Chaharmahal Va Bakhtiari, Iran (Figure 1).

Hawthorn forests in the present study area are distributed between 1 500 and 2 400 m in altitude. The mean annual precipitation and temperature of the area are 330 mm and 14 °C, respectively. Forest stands are relatively uniform in size and age as well as extensively dominated by Persian oak with the basal area ranging between 57.70 and 113.23 m²·ha⁻¹. Due to their remote location and the absence of evidence of human impact, it is assumed that all stands have developed under the influence of natural impacts and disturbances. The maximum rooting depth is frequently limited by the shallow bedrock. In each circular plot, all live trees of 7.5 cm diameter at breast height at least (DBH, height at 1.30 m above the ground) were identified, and their diameter at breast height, height, crown length, and crown perpendicular diameters were recorded within 0.1 ha area. The calliper, Vertex and diameter tape were used to measure tree DBH, height and crown diameters, respectively. In each plot, one healthy dominant tree with the largest DBH without any defects and reaction wood were sampled, and one disk was taken from the tree trunk at DBH for the determination of wood properties. Then stand-level variables such as stand basal area, stand density, stand quadratic mean diameter (QMD), and tree-level variables such as stem basal area, stem volume, tree crown diameter and tree crown basal area in each ecosite were calculated based on the data on 27 circular 0.1 ha sample plots. The tree crown diameter was measured as the average crown spread which is the average of the lengths of the longest spread from edge to edge across the crown and the longest spread perpendicular to the first cross-section through the central mass of the crown. The tree crown basal area as tree crown area projection was calculated based on the crown area as a circle using the average crown spread as its diameter. The tree age at breast height (ABH) was ob-

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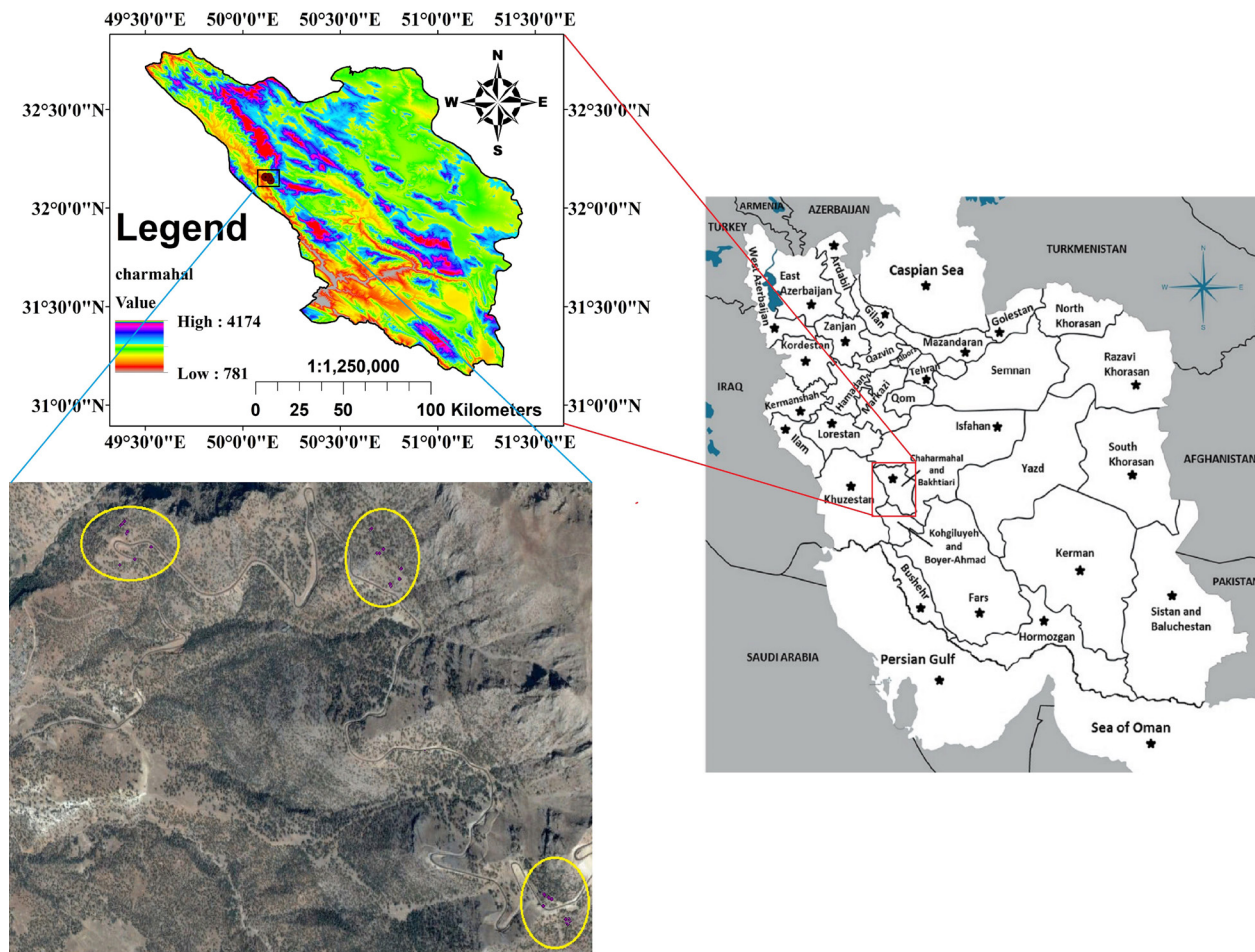


Figure 1. Location of the study area, three forest stands and 27 sampling plots at nine study ecosites in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran

tained by counting the annual rings of the sampled disks. Finally, the mean annual diameter increment (MADI) was obtained by dividing DBH by the number of annual rings.

The annual records of total precipitation and mean annual temperature, the main climatic factors affecting the wood properties and tree growth parameters in the region were obtained from the Koohrang Synoptic Meteorological Station (32.46°N, 50.13°E; 2 365 m a.s.l.) (Chaharmahal Va Bakhtiari Meteorological Administration 2020). Site conditions, tree characteristics and descriptive statistics for the studied variables of hawthorn (*Crataegus azarolus*) wood sample trees and forest stands in the study area are presented in Table 1.

Physical properties. Five cm thick disks were obtained from the logs for the determination of physical properties. In detail, specimens with di-

mensions of $3 \times 2 \times 2 \text{ cm}^3$ were prepared in accordance with ISO 13061-14 (2016) for the investigation of oven-dry density and volumetric shrinkage. In total 270 specimens from different parts of disks (10 specimens per each disk) were prepared.

Sample dimensions were measured in green (saturated) and oven-dry condition with a slide calliper; oven-dry mass was determined with an electric balance to the nearest 0.01 g. The volumetric shrinkage was calculated using the dimensional change from the green to oven-dry condition. The physical properties were calculated according to the following equations:

$$D_0 = \frac{P_0}{V_0} \tag{1}$$

$$\alpha_V = \frac{V_S - V_0}{V_0} \tag{2}$$

where:

D_0 – oven-dry density ($\text{g}\cdot\text{cm}^{-3}$);

α_v – volumetric shrinkage (%);

V_s – volume in saturated state (cm^3);

V_0 – volume in oven-dry state (cm^3);

P_0 – mass in oven-dry state (g).

Morphologic properties. Separation of individual wood fibres was performed using the Franklin method (1945) in this way: wood specimens with the dimensions of $15 \times 10 \times 2 \text{ mm}^3$ were saturated in a mixture (1 : 1) of acetic acid and oxygenized water in test tubes. Afterward, the specimens were kept in an oven at $65 \pm 3 \text{ }^\circ\text{C}$ for 48 hours. After maceration, the specimens were washed (2–3 times) in distilled water. Then they were immersed into distilled water, shaken, and the fibre parameters (fibre length, fibre

diameter, and cell wall thickness) were evaluated under a light microscope. From each slice, at least 50 fibres were used for the measurements.

Statistical analysis. Primary statistical analysis was performed for the input variables to enter the statistical analysis process. Normal distribution of data is one of the preconditions of the multivariate analysis of variance (MANOVA). Therefore, data sets were tested for normal distribution using the Shapiro-Wilk test of normality, and then data transformation was applied to those that were not normally distributed. Levene's test was employed to examine the homogeneity of variances. MANOVA was conducted to evaluate significant differences between the mean values of studied wood properties at altitude levels and slope classes using the statistical package for social sciences (SPSS 23) (IBM, Armonk,

Table 1. Site conditions and tree characteristics at nine different ecosites collected in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran

Ecosites	E1S1	E1S2	E1S3	E2S1	E2S2	E2S3	E3S1	E3S2	E3S3	
Latitude (N)	3558132	3558227	3558354	3558250	3558120	3558137	3556272	3556280	3556299	
Longitude (W)	416662	416867	416680	418209	418248	418284	419180	419165	419138	
Altitude (m a.s.l.)	1 717	1 726	1 742	1 980	1 987	1 968	2 280	2 244	2 232	
Mean annual precipitation (mm)	331	330	329	330	329	328	329	330	330	
Mean annual temperature ($^\circ\text{C}$)	15.3	15.2	15.3	14.5	13.9	13.0	12.8	12.9	12.9	
Stand-level variables	stand basal area	39.20	96.28	42.56	36.12	61.56	81.48	60.72	59.00	62.93
	stand density	140	116	112	84	108	78	132	100	110
	QMD	59.72	102.83	69.58	74.01	85.21	115.65	76.55	86.69	85.21
Tree-level variables	DBH	58.67 (11.37)	101.00 (23.52)	69.33 (6.51)	73.33 (12.34)	85.00 (7.00)	109.67 (45.35)	75.33 (16.50)	84.33 (27.02)	84.67 (10.69)
	height	4.48 (0.36)	8.71 (0.54)	5.13 (0.71)	4.86 (1.63)	6.20 (1.59)	7.25 (3.46)	4.84 (1.44)	5.63 (0.29)	10.76 (5.23)
	stem basal area	0.28 (0.10)	0.83 (0.37)	0.38 (0.07)	0.43 (0.15)	0.57 (0.09)	1.05 (0.84)	0.46 (0.20)	0.59 (0.36)	0.57 (0.15)
	stem volume	0.64 (0.27)	3.77 (1.82)	1.00 (0.15)	1.13 (0.66)	1.83 (0.75)	4.78 (5.62)	1.26 (0.83)	1.75 (1.10)	3.28 (2.35)
	ABH	298 (30)	447 (95)	323 (10)	335 (30)	360 (13)	468 (180)	339 (34)	380 (91)	369 (36)
	crown diameter ¹	2.58 (0.21)	4.65 (0.58)	4.62 (0.39)	5.23 (0.71)	4.25 (0.30)	4.78 (0.58)	4.25 (0.58)	4.77 (1.26)	5.97 (1.08)
	crown basal area	5.26 (0.83)	17.15 (4.09)	16.81 (2.87)	21.76 (5.94)	14.23 (2.00)	18.14 (4.50)	14.35 (3.82)	18.66 (8.85)	28.56 (10.00)
	MADI (mm)	1.96 (0.19)	2.25 (0.06)	2.14 (0.14)	2.18 (0.16)	2.36 (0.12)	2.33 (0.16)	2.20 (0.27)	2.19 (0.24)	2.29 (0.07)

QMD – quadratic mean diameter; DBH – diameter at breast height; ABH – age at breast height, MAI – mean annual diameter increment; ¹crown width in m measured from below the tree in the field; standard deviations are in parentheses; MADI – mean annual diameter increment

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USA). This method generated a multivariate dataset that was interpreted by using principal component analysis (PCA). The patterns of variation of the measured traits were selected and used for performing PCA based on the method of alternating least squares (PRINQUAL procedure in SAS). A Kruskal secondary least-squares monotonic transformation was applied to all variables, with the restriction that ties were preserved. Results were presented by a PCA biplot that showed the transformed variables (e.g. the measured traits) projected onto the two-dimensional plane of the analysis described by the two principal components. PCA is a classical multivariate (unsupervised machine learning) statistical method that is used to interpret the variation in a high-dimensional interrelated dataset (dataset with a large number of variables). PCA reduces the high-dimensional data to low-dimension by linearly transforming the old variable into a new set of variables called principal component (PC) while retaining the most possible variation. The PCs are easy to visualize and summarise the features of original high-dimensional datasets in low-dimensional space. PCA allowed the multivariate dataset to be reduced by minimizing multicollinearity and associating the correlated variables in two principal axes (Rossi et al. 2015). This approach improved data exploration and simplified the interpretation of the results.

RESULTS AND DISCUSSION

Physical properties

Oven-dry density. It is known that there are several factors affecting the density of the wood. These factors include anatomical properties, e.g. vessel and fibre morphology, ecological site, moisture content, and chemical composition (Wagenführ, Scheiber 1995; Pásztor et al. 2014; Zeidler, Borůvka 2016; Bahmani et al. 2020). The mean values of oven-dry

density determined for hawthorn wood at three different altitude levels and slope classes are presented in Table 2. MANOVA results revealed significant differences between the mean values of oven-dry density at altitude levels while it found no statistically significant difference at different slope classes (Table 3). Interaction impacts of altitude and slope show a significance of oven-dry density (Table 3). The highest ($0.78 \text{ g}\cdot\text{cm}^{-3}$) and the lowest ($0.66 \text{ g}\cdot\text{cm}^{-3}$) values of oven-dry density were identified at the intermediate altitude level in the second slope class and at the high altitude level in the first slope class, respectively. Overall, the mean value of oven-dry density of $0.72 \text{ g}\cdot\text{cm}^{-3}$ was obtained for hawthorn wood which was found to be higher than that of hornbeam wood and about equal to that of oriental beech as reported by Kiaei et al. (2019) and Topaloglu et al. (2016), respectively. The average of oven-dry density decreased with increasing elevation. A similar finding was reported by Topaloglu et al. (2016) for oriental beech and by Kiaei et al. (2019) for *C. betulus*.

Volumetric shrinkage. Volumetric shrinkage is a physical property that significantly affects the wood and wood product usability. It is generally dependent on the wood density (Guler et al. 2007). Table 2 shows the mean values of volumetric shrinkage for hawthorn wood. From the MANOVA test it can be derived that the effect of altitude on volumetric shrinkage is significant at the 0.01 significance level but the effect of slope on volumetric shrinkage is not significant (Table 3). The interaction of altitude and slope classes has no statistically significant effect on volumetric shrinkage (Table 3). The highest (21.74%) and the lowest (10.92%) values of volumetric shrinkage were found at the intermediate altitude level in the third slope class and at the high altitude level in the third slope class, respectively. Overall, the mean value of volumetric shrinkage of 18.31% was determined.

Table 2. The means (with standard deviations in parentheses) of physical properties of hawthorn wood at three different altitudes and slope classes in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran

Wood properties	Altitude (m)/slope (%)								
	below 1 800 (low)			1 800–2 000 (intermediate)			above 2 000 (high)		
	< 30%	30–45%	> 45%	< 30%	30–45%	> 45%	< 30%	30–45%	> 45%
Oven-dry density ($\text{g}\cdot\text{cm}^{-3}$)	0.75 (0.01)	0.67 (0.04)	0.68 (0.04)	0.74 (0.02)	0.78 (0.01)	0.73 (0.04)	0.66 (0.06)	0.71 (0.01)	0.72 (0.02)
Volumetric shrinkage (%)	19.33 (0.24)	19.13 (5.95)	19.91 (1.51)	19.86 (0.06)	20.01 (1.00)	21.74 (2.65)	12.53 (2.71)	12.63 (7.29)	10.92 (6.30)

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Table 3. The means (with standard deviations in parentheses) of fibre morphology of hawthorn wood at three different altitudes and slope classes in the Bazoft region forest of Chaharmahal Va Bakhtiari, Iran

Wood properties	Altitude (m)/slope (%)								
	below 1 800 (low)			1 800–2 000 (intermediate)			above 2 000 (high)		
	< 30%	30–45%	> 45%	< 30%	30–45%	> 45%	< 30%	< 30%	30–45%
Fibre length (mm)	0.72 (0.02)	0.93 (0.53)	0.85 (0.49)	0.69 (0.24)	0.57 (0.12)	0.88 (0.08)	0.87 (0.50)	0.81 (0.04)	0.87 (0.03)
Fibre diameter (µm)	21.48 (1.27)	18.91 (0.06)	22.41 (0.05)	20.02 (0.15)	19.43 (0.44)	20.53 (0.48)	19.07 (11.01)	19.94 (0.12)	19.96 (0.33)
Cell wall thickness (µm)	5.82 (0.07)	5.89 (0.12)	5.58 (0.18)	5.92 (0.11)	5.76 (3.32)	6.10 (0.08)	5.56 (0.19)	5.54 (0.17)	5.92 (0.01)

As is well known, the relationship between wood density and volumetric shrinkage is positive (Sousa et al. 2018). A similar finding was reported by Kiaei (2012) for *Carpinus betulus*. However, swelling cannot be fully explained by density, as the wood with the medium and highest density has comparable density, but shrinkage differs significantly. Possible reasons that could affect the shrinkage are: dimensions of the cells, chemical composition as well as sorption properties (Hunter 1996). As this topic has not been fully addressed in literature, we will emphasize it in one of the future studies.

Morphologic properties

Fibre length. Fibre morphology is one of the factors that influence the qualitative and quan-

titative wood properties (Panshin, Zeeuw 1980; Kiaei 2012). The mean values of the parameter fibre lengths for hawthorn wood at three different altitude levels and slope classes are presented in Table 4. The highest (0.93 mm) and the lowest (0.57 mm) mean values of fibre length were found at the low altitude level in the second slope class and at the intermediate altitude level in the second slope class, respectively. Mean values of fibre length (0.78 mm) were achieved in total. According to the results of MANOVA, altitude has a statistically significant effect on the fibre length at the 95% confidence interval while slope variation has no significant effect (Table 3). Interaction impacts of altitude and slope show a significant effect on fibre length at the 95% confidence interval (Table 3).

Table 4. Multivariate analysis of variance (MANOVA) results of wood physical properties and fibre dimensions

Source of variation	Wood properties	Sum of squares	df	Mean square	F	Sig.
Altitude	oven-dry density	0.019	2	0.009	8.346	0.003**
	fibre length	0.100	2	0.050	5.252	0.016*
	fibre diameter	7.960	2	3.980	16.284	0.000**
	cell wall thickness	0.294	2	0.147	9.110	0.002**
	volumetric shrinkage	387.735	2	193.868	32.681	0.000**
Slope	oven-dry density	0.002	2	0.001	0.701	0.509 ^{ns}
	fibre length	0.061	2	0.030	3.181	0.066 ^{ns}
	fibre diameter	10.612	2	5.306	21.709	0.000**
	cell wall thickness	0.089	2	0.044	2.757	0.090 ^{ns}
	volumetric shrinkage	0.478	2	0.239	0.040	0.961 ^{ns}
Altitude × slope	oven-dry density	0.027	4	0.007	6.128	0.003**
	fibre length	0.165	4	0.041	4.330	0.013*
	fibre diameter	12.488	4	3.122	12.773	0.000**
	cell wall thickness	0.519	4	0.130	8.047	0.001**
	volumetric shrinkage	12.443	4	3.111	0.524	0.719 ^{ns}

*, **Significant at the 0.05 and 0.01 significance level; ^{ns}not significant

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The mean value of fibre length increased with increasing altitude. Similar observations were previously reported by Noshiro et al. (1995) for *Alnus nepalensis*, Yilmaz et al. (2008) for *Quercus pontica* and Kiaei et al. (2019) for *Carpinus betulus*.

According to Wheeler et al. (1989) fibres are classified into three classes: (1) short fibres with a length of less than 0.90 mm; (2) fibres of medium length between 0.90 and 1.90 mm including hawthorn wood with an average fibre length of 0.95 mm; (3) fibres longer than 1.90 mm. The measured average fibre length of hawthorn wood is lower than that reported for most hardwoods (Horn 1987).

Fibre diameter. Fibre diameter depends on exogenous growth conditions and annual ring width (Zobel, Van Buijtenen 1989). A maximum value of 22.41 μm and a minimum value of 19.07 μm for fibre diameter were determined at the low altitude level in the third slope class and at the high altitude level in the first slope class, respectively (Table 4). Overall, mean values of fibre diameter of 20.24 μm were in agreement with the values reported for other hardwood fibres (Atchison 1987). MANOVA test results indicate statistically significant differences in the mean values of fibre diameter between altitude levels and slope classes at the 99% confidence interval (Table 3). Plomion et al. (2001) reported that the variations in the fibre diameter depend on molecular and physiological changes occurring in the vascular cambium as well as in the wood cell walls throughout the tree growth. Interaction impacts of altitude and slope show a statistically significant effect on fibre diameter (Table 4).

Cell wall thickness. Cell wall thickness is variable among species, sites, between and within trees as well as highly correlated with wood density. A positive correlation between wood density and cell wall thickness is described by many types of research, e.g. by Horn (1978) and Topaloglu et al. (2016). The maximum mean value of the parameter cell wall thickness (6.10 μm) as well as the minimum (5.54 μm) was determined for the selected hawthorn wood at the intermediate altitude level in the third slope class and at the high altitude level in the second slope class, respectively (Table 4). In total, the mean value of cell wall thickness of 5.79 μm was determined. MANOVA results in Table 4 revealed that altitude had a significant impact on the parameter cell wall thickness at the 99% confidence interval while slope had no significant effect (Table 3). Interaction impacts of altitude and

slope show a statistically significant effect on cell wall thickness (Table 3).

In summary, the evaluation of the characteristic values revealed a statistically significant effect of altitude on all studied wood properties and slope had a statistically significant effect on the fibre diameter at the 0.01 significance level. However, there were significant effects from the interaction of altitude and slope on all studied wood properties except volumetric shrinkage (Table 3).

Relationship between wood properties and site conditions

Principal component analysis. Principal component analysis (PCA) was applied as one of the dimensionality reduction techniques that reduce the difficulties in interpreting high- and low-dimensional signals. When the data are distributed in a multidimensional space, it is possible to define an axis that can reduce the dimension most efficiently and focus on the dimension of that axis. In other words, it is essential to find the optimal axis among several axes, and the PCA can obtain the exact axis. Figure 2 shows the PCA scree plot of the studied variables.

The results of Kaiser-Meyer-Olkin (KMO = 0.59) and Bartlett's test of sphericity ($P < 0.01$) confirmed the adequacy of the data set for PCA. The transformed variables of the measured traits were projected onto two-dimensional planes generated by the first two canonical axes (Figure 4). Graph of study variables and biplot of sample plots as well as study variables based on the first and second components are presented in Figure 4 and Figure 3. The first four PCs (6D) contribute ~71.25% of the total variation in the dataset and have eigenvalues > 1 , and thus provide a good approxima-

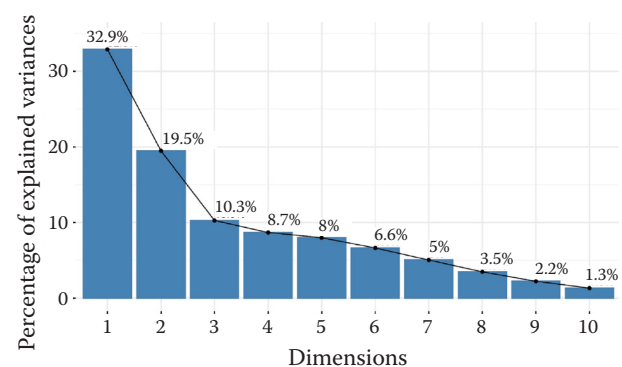


Figure 2. Scree plot for selecting the optimal number of components

tion of the variation present in the original 18D dataset (see the cumulative proportion of variance and scree plot in Table 5 and Figure 2). The cut-off of cumulative 70% variation is common to retain the PCs for analysis (Jolliffe, Cadima 2016). Even though the first four PCs contribute ~85.93% and have eigenvalues > 1, it will be difficult to visualize them at once and it needs to perform pairwise visualization (Table 5).

Canonical axis 1 represented 32.90% of the variability, while the variance accounted for by canonical axis 2 and axis 3 represented 19.42% and 10.23% of the variability, respectively (Figure 3 and Table 5). The analysis of the PCA shows that three components explain 62.54% of the total variance (Table 5). Similar directions with respect to the origin revealed high correlations between the variables of the measured traits. This is related to the parameters volumetric shrinkage, fibre diameter and cell wall thickness. Total variance explained by six principal components is 85.93% (Table 5 and Figure 3).

The first component explains 32.90% of the total variance. It is most highly correlated with the

growth parameters tree basal area, DBH, tree age, tree volume, tree height, mean annual tree diameter increment. These variables are not notably correlated with the other principal components. The second component describes 19.42% of the variance mainly influenced by the parameters tree crown basal area and tree crown diameter. The third component explains 10.23% of the total variance relating to the parameters altitude, temperature, volumetric shrinkage, cell wall thickness and fibre diameter. The fourth component describes 8.71% of the variance influenced by the parameters fibre length and oven-dry wood density. The fifth component explains 8.02% of the variance influenced by the settings precipitation and slope, and the sixth component explains 6.67% of the total variance relating to the parameter critical density (Tables 5 and 6, Figures 3 and 4).

From the biplot and loadings plot, we can see the variables tree basal area, tree age, tree volume, DBH, tree height, cell wall thickness, oven-dry density and volumetric shrinkage are highly associated and form a cluster (effects on the response of wood properties in relation to these variables are

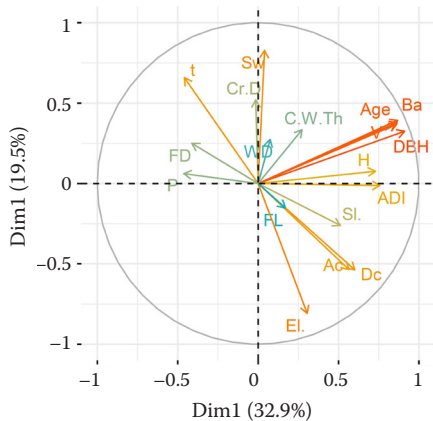


Figure 3. Graph of study variables based on the first and second components

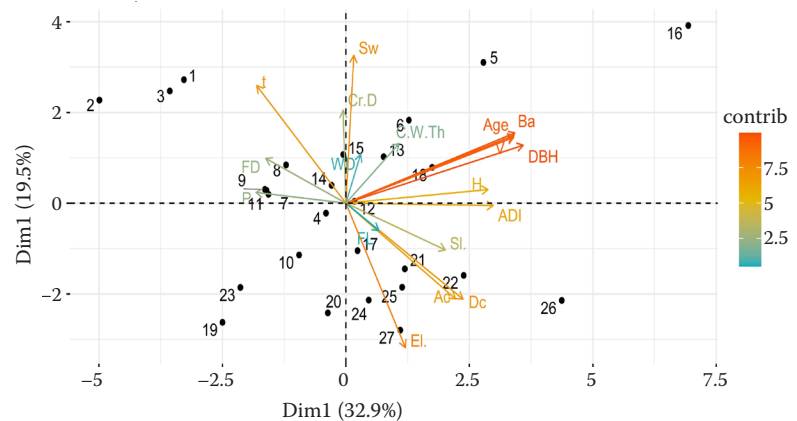


Figure 4. Biplot of sample plots and study variables based on the first and second components

Dc – crown diameter, crown width in m measured from below the tree in the field; population-level mean of tree-level mean fibre length weighted by basal area; population-level mean of tree-level standard deviation of fibre length calculated from a weighted variance function; DBH – tree diameter at breast height (cm); Age – tree age at breast height (year); ADI – mean annual diameter increment (mm); Ba – stem basal area (m²); V – stem volume (m³); Ac – crown basal area (m²); El. – altitude (m a.s.l.); Sl. – slope (%); P – mean annual precipitation (mm); t – mean annual temperature (°C); WD – oven-dry wood density (g·cm⁻³); Sw – volumetric shrinkage (%); FD – fibre diameter (µm); FL – fibre length (mm); C.W.Th – cell wall thickness (µm); Cr.D – critical density; Dim1 – first component; Dim2 – second component; contrib – variance explained by traits on the first and second components; PCA – principal and second components; 1–27 – sample plots

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Table 5. Total variance explained and calculated eigenvalues for the principal components

Component	Total variance explained		
	initial eigenvalues		
	total	% of variance	cumulative %
1	5.921	32.896	32.896
2	3.495	19.417	52.313
3	1.841	10.229	62.542
4	1.568	8.709	71.251
5	1.443	8.016	79.266
6	1.200	6.667	85.933
7	0.900	4.998	90.931
8	0.617	3.430	94.362
9	0.400	2.220	96.582
10	0.236	1.313	97.894
11	0.202	1.121	99.015
12	0.087	0.484	99.499
13	0.053	0.293	99.792
14	0.023	0.130	99.923
15	0.009	0.049	99.971
16	0.004	0.020	99.991
17	0.002	0.009	100.000
18	5.885E-5	0.000	100.000

highly similar). Similarly, temperature, precipitation, fibre diameter and critical density are highly associated and form another cluster (effects on the response of wood properties in relation to these variables are highly similar but different from other clusters). Similarly, altitude, tree crown diameter, tree crown basal area, tree mean annual diameter increment (MADI), slope and fibre length are highly associated and form another cluster (effects on the response of wood properties in relation to these variables are highly similar but different from other clusters). If the variables are highly associated, the angle between the variable vectors should be as small as possible in the biplot. The length of PCs in the biplot refers to the amount of variance contributed by the PCs. The longer the length of PC, the higher the variance contributed and well represented in space.

Contributions of variables to first and second principal components are presented in Figure 5 and Figure 6. Results showed that DBH, tree basal area, tree age, tree volume, tree mean annual diameter increment, tree height and tree crown diameter had most contributions to the first principal component (Figure 5). According to Figure 6, volumetric

Table 6. Factor load variables in each of the principal components

	Component					
	1	2	3	4	5	6
Altitude	0.033	0.236	-0.912*	0.042	0.041	-0.201
Slope	0.151	0.602	-0.075	-0.197	0.625*	0.203
Precipitation	-0.305	-0.036	0.110	0.068	-0.860*	0.213
Temperature	-0.208	-0.183	0.850*	-0.034	-0.259	0.138
DBH	0.964*	0.121	-0.002	0.031	0.137	-0.007
Tree Height	0.652*	0.486	-0.015	-0.173	-0.217	0.283
Tree crown diameter	0.178	0.910*	-0.189	-0.014	0.086	-0.188
Tree basal area	0.965*	0.028	0.030	0.014	0.151	0.019
Tree crown basal area	0.142	0.931*	-0.182	0.015	0.017	-0.135
Tree Volume	0.937*	0.133	0.049	-0.060	0.027	0.125
Tree Age	0.962*	0.045	0.043	-0.045	0.102	-0.005
Tree mean annual diameter increment	0.619*	0.385	-0.147	0.242	0.183	-0.048
Oven-dry Density	0.119	0.041	-0.013	0.851*	-0.131	0.355
Fiber length	0.120	0.077	-0.093	-0.865*	0.017	0.177
Fiber diameter	-0.460	-0.001	0.464*	-0.052	0.462	0.407
Cell wall thickness	0.319	0.205	0.478*	0.091	-0.054	-0.251
Critical density	0.180	-0.198	0.135	0.087	-0.096	0.880*
Volumetric shrinkage	0.285	-0.295	0.766*	0.270	0.327	-0.073

* Features that contributed most for Axes 1–5. Extraction method: Principal Component Analysis. Rotation Method: arimax with Kaiser Normalization. A rotation converged in 5 iterations

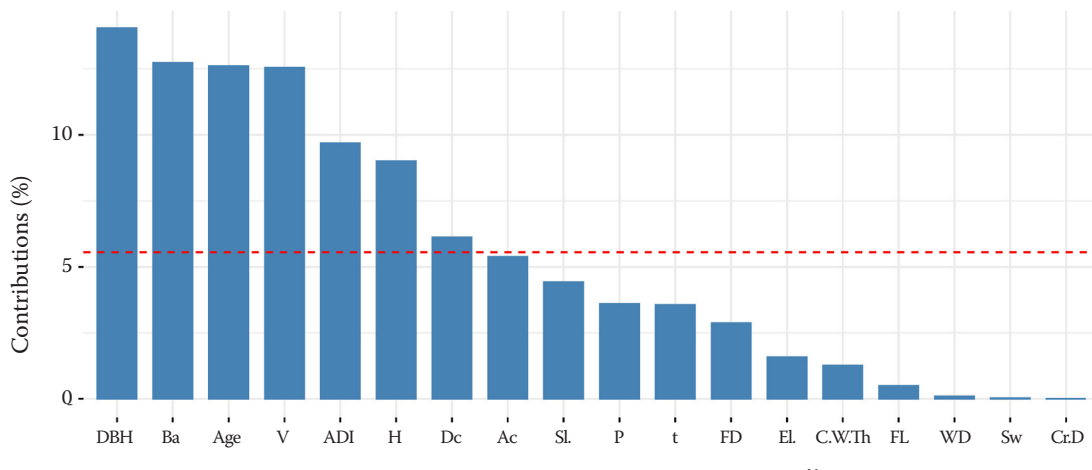


Figure 5. Contributions of variables to the first principal component

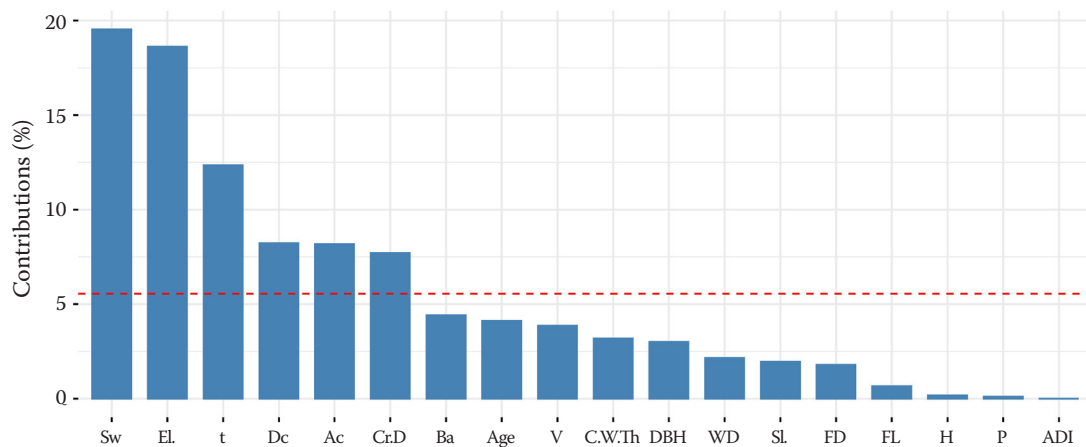


Figure 6. Contributions of variables to the second principal component

shrinkage, altitude, temperature, tree crown diameter, tree crown basal area and critical density had most contributions to the second principal component. Summarizing, PCA shows noticeable variations of wood properties in the study site across altitude and slope gradient. Since these methods are of high accuracy and have different abilities, they could be used for habitat analysis and determination of effective ecological factors. Analysing ecological data by ordination methods provides more straightforward understanding of the complicated relationship between growth parameters, wood properties and environmental gradients. Besides, these methods are impaired by the existence of ineffective factors and the data complexity of ecological methods. By using PCA, not only the number of comparisons between treatment means is reduced, but also the meaningfulness of these comparisons is enhanced. In the present study, multivariate anal-

ysis is used to identify obvious differences in wood properties and the selected variables. The obtained results show that the first axis has the highest correlation with tree-level variables, and the second axis has the highest correlation with the parameters of wood properties, altitude and temperature. Comparable results have been reported by many investigations (Noshiro et al. 1995; Yılmaz et al. 2008; Kaygin et al. 2016; Kiaei et al. 2019)

As mentioned above, the location of the wood properties, tree characteristics and forest stand variables in different regions of PCA axes is based on correlation coefficients between the variables. Therefore, the location of the variables in Figure 3 is significant and important. For example, the forest stand variables and wood properties that occupied a specific region and are close to each other have several similar characteristics between each other and consequently the correlation coefficient between those

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characteristics occupies opposite places in Figure 3; for example, opposite directions of an axis show distinct variations. Further work is required to examine the anatomical properties (fibre proportions, rays, vessels and parenchyma), ring width and cambial age changes with the variations of the geographic factors.

CONCLUSION

In this study, the properties of hawthorn wood were examined at different elevations above sea level and slope classes. The following conclusions were obtained:

- There were statistically significant differences in the parameters oven-dry density, fibre length, fibre diameter and the cell wall thickness of hawthorn wood at various altitudes. In contrast, no significant differences were found between the mean values of volumetric shrinkage.
- There were statistically significant differences in the parameters fibre diameter of hawthorn wood at different slope classes while no significant differences were found between the mean values of oven-dry density, fibre length and cell wall thickness.
- The highest mean values of oven-dry density, volumetric shrinkage, fibre diameter and cell wall thickness were found at the low altitude. However, the highest mean value of fibre length was detected at the high altitude level.
- The altitude, precipitation and temperature are the most important environmental site variables affecting the wood characteristics as shown by PCA analysis.
- More research is required to further interpret our results and to better explain the relationship between ecological factors and properties of hawthorn wood.

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