

EFFECTS OF ALTITUDE AND SEASONAL VARIATION ON STEM MOISTURE CONTENT AND RADIAL DISTRIBUTION IN SCOTS PINE AND ORIENTAL BEECH

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ABSTRACT

The stem moisture content (MC) of living trees governs log weight, drying behavior, preservative uptake, and the susceptibility of timber to checking and decay, while also reflecting the response of the tree to climate. This study aimed to evaluate monthly variations in the stem MC of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) at two altitudes and examine the relationships between stem MC and environmental factors such as air humidity, temperature, and soil moisture. Stems were sampled monthly over a full annual cycle at two contrasting altitudes in the Andes. The cross-sections were partitioned into radial zones, and the air temperature, relative humidity, and soil moisture were recorded in parallel. Altitude and sampling month significantly affected stem MC for both species. The annual mean reached 57% at high altitudes versus 50% at low altitudes in Scots pine (*Pinus sylvestris* L.) and 70% versus 58% in oriental beech (*Fagus orientalis* Lipsky). Stem MC peaked in October-December and February-March, and fell to its annual minimum during summer. Radially, MC in Scots pine (*Pinus sylvestris* L.) increased from the bark towards the inner sapwood (mean $\approx 85\%$) and then dropped sharply to $\approx 35\%$ in the heartwood, with the sapwood-heartwood contrast widening at higher altitudes. Oriental beech (*Fagus orientalis* Lipsky) showed a more gradual gradient (sapwood $\approx 79\%$, heartwood $\approx 55\%$), and at lower altitudes, the two zones became virtually indistinguishable in some summer months. Stem MC was positively correlated with soil moisture in both species. Oriental beech (*Fagus orientalis* Lipsky) additionally showed a positive correlation with relative humidity and a strong negative correlation with air temperature, whereas scots pine (*Pinus sylvestris* L.) MC was not associated with atmospheric variables. Therefore, altitudinal origin and felling month carry a predictable signal of log moisture, with direct consequences for transport, drying, impregnation, and defect management. January felling emerged as the most favorable window, and the dataset supports fire risk modelling, biomass energy calculations, and drought stress assessments for two ecologically and economically important species.

Keywords: Altitudinal gradient, environmental factors, radial moisture distribution, soil moisture, wood moisture dynamics

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INTRODUCTION

Scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) are important tree species used naturally and for impregnation in many areas of the wood industry. Scots pine (*Pinus sylvestris* L.) is a taxon with a wide climatic and edaphic range throughout the Eurasian continent, from 37°N to 70°20'N (Mátyás *et al.* 2004). In Turkey, which is its southernmost border (Kayacık 1980), scots pine (*Pinus sylvestris* L.) is found in pure and mixed forms over an area of 1,46 million hectares (GDF 2024). Oriental beech (*Fagus orientalis* Lipsky) has the largest geographical distribution in Turkey (1,9 million hectare), followed by Bulgaria, Greece, Crimea, Caucasus, and Iran. In Turkey, north-facing slopes along the Black Sea provide the most suitable growing conditions for this species (Yaltırık 1982). According to the average of the last ten years 3,3 million cubic meters of oriental beech (*Fagus orientalis* Lipsky) (36 % as logs) and 1,5-2 million cubic meters of scots pine (*Pinus sylvestris* L.) (35 % as logs) are produced annually in Turkey (GDF 2024). These species, which have low natural durability, can deteriorate after log production under the influence of many biotic and abiotic factors, and their quality characteristics can decrease in a short time. One of the variables that most directly governs this process – and that simultaneously underlies log weight, drying behaviour, preservative uptake and the physiological water status of the standing tree – is the stem moisture content (MC; green moisture content of the stem or log).

Oriental beech (*Fagus orientalis* Lipsky) wood has a diffuse-porous structure, with its conducting vessels distributed homogeneously throughout the growth ring. Additionally, since it does not exhibit prominent heartwood formation and is largely characterized as sapwood, the trunk as a whole is highly sensitive to water conduction and changes in moisture. These anatomical features directly affect the wood's moisture behavior (Schweingruber 1990).

Although the moisture content (MC) of trees varies within species (Haygreen and Bowyer 1996), factors such as the location of growth of these species, stand structure, site quality, soil moisture content, season and age of trees, dendrometry, and densitometry have an important influence on MC (Ward and Pong 1980, Constant *et al.* 2002). MC can vary along the length and radial direction of each stem (Chen *et al.* 1998). Studies have shown that the distribution of moisture across the radial section of the tree stem is evaluated by dividing it into three zones in some studies (Nakada *et al.* 1999b) and into five zones in others (Nakada *et al.* 1999a, Constant *et al.* 2002, Chiu and Lin 2007), depending on the classification approach used. Radially, a marked variation from the outside to the inside was observed owing to the active water conduction of the sapwood and the inactive water conduction structure of the heartwood (Gartner *et al.* 2004). Beyond these spatial patterns, stem MC also tracks short-term climatic variability: air temperature, vapor pressure deficit, relative humidity, and soil water content jointly regulate transpiration, sap flow, and xylem water storage, and these processes translate into measurable seasonal fluctuations in the water held in the living stem (Köcher *et al.* 2009, Oberhuber *et al.* 2023).

Variables that occur in the anatomical structure of a tree during its development could effectively change stem MC. Passage aspiration in conifers and veil formation in broadleaved species are among the most important reasons for stem MC differences. In addition, it has been found that the conductive elements of wood are filled with various extractives, resins, etc. in the heartwood section, which prevents water conduction (Koch 1972, Tsoumis 1991). Regardless of the differences in the anatomical structures of the tree's woody trunk, it has been reported that the presence of soil moisture directly affects the moisture content of tree stem wood by controlling the dynamics of water storage and uptake in the xylem, and this effect is closely related to changes in sap flow and hydraulic conductivity (Matheny *et al.* 2015). What remains comparatively unexplored, however, is the way in which altitude reshapes this annual MC signal through its coupled effect on temperature, precipitation, evaporative demand, growing-season length and the timing of soil-moisture recharge (Körner 2007, Song *et al.* 2016, Pacheco *et al.* 2018). For Scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky), particularly at the southern margin of their ranges, most existing MC datasets are restricted to a single felling event, to growing-season campaigns, or to laboratory-equilibrated specimens, and therefore do not capture the combined effect of altitude and season on living-stem water.

To address this gap, the present study was designed around year-round destructive sampling at contrasting altitudinal positions for both species, paired with continuous monitoring of air temperature, relative humidity and soil moisture content. A full annual cycle was preferred to a growing-season-only campaign so that dormant-period dynamics, when transpiration is reduced and soil water is replenished, could be quantified alongside the high-demand summer months. Within this framework, the main objectives of the study are:

- to investigate the changes in stem MC throughout the year in scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky), two commercially important species sampled at contrasting altitudes;
- to describe the radial distribution of MC across the stem cross-section of each species and to test how this radial pattern is modulated by altitude and season;
- to determine the correlations between stem MC and ambient air temperature, relative humidity and soil moisture content.

The principles used to determine the physical properties of living trees are strongly influenced by stem MC. A clearer description of how trunk MC changes throughout the year, in the radial direction and across altitudinal positions will therefore contribute to the reliability of these test methods and to the interpretation of tree water status under increasingly variable climate conditions.

In practical terms, knowledge of the seasonal stem MC of the species under study is essential for estimating the approximate green density of logs and for providing reliable data to timber producers. Because water typically accounts for around half of the weight of a freshly felled log, the resulting information will help both the forest enterprises producing logs and the companies responsible for processing, drying and impregnating them to organize their operations on a more realistic basis. The same dataset will further support forest-fire risk assessment, biomass-energy yield estimation, and the analysis of tree physiology and drought stress in two species of high economic and ecological importance.

MATERIAL AND METHODS

In this study, we investigated the monthly variation in stem MC of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) growing at different altitudes. In this context, two sampling plots were selected at different altitudes in pure oriental beech (*Fagus orientalis* Lipsky) and Scots pine (*Pinus sylvestris* L.) stands in the Düzce region of Türkiye. When selecting the sampling areas, the orientation of the terrain was considered, and both the lower and upper areas were positioned in the northeast direction. For the monthly measurements, increment cores were taken from four trees in each group (combination of tree species and altitude) to measure moisture; three of these cores were taken from the same individuals each month, whereas the fourth was taken each month from a different individual. Thus, 16 trees were measured each month for all the altitudes and tree species. Trees were selected by visual assessment, and care was taken to ensure that they were representative of the stand, in the dominant layer, and indicative of future tree characteristics. No visible stem defects, dry branches, or dry or discolored leaves were observed. The data on sampling plots and tree species are presented in Table 1.

Monthly average air temperature and relative humidity measurements were taken by placing data loggers capable of measuring every 4 h in the sampling plots. At the end of the measurement, data were collected in the field and analyzed using the data loggers. In addition, to examine the monthly changes in soil moisture from each sampling area, two separate bags of soil samples were taken from 10 cm (P10) and 30 cm (P30) depths and transported to the laboratory. The fresh weights of the soils were measured in the laboratory, dried at 103 °C, and reweighed to calculate the gravimetric moisture content of the soil.

According to the average climate data of Düzce Province, where the sampling areas are located, between 1959 and 2023, the average air temperature was 13.2 °C and the total annual precipitation was 838 mm. The vegetation period is between Apr and Oct, and the precipitation is 422 mm (GDM 2024).

Table 1: Information on sampling areas and tree species

Sampling areas	Tree species	Mean tree height (m)	d _{1.30} tree diameter (cm)	Mean tree age (year)	Altitude (m)	Geographical location
High altitude (HA)	Scots pine	20	35	59	1290	40°41'38"N 31°21'25"E
	Oriental beech	20	31	61	1288	40°41'38"N 31°21'30"E
Low altitude (LA)	Scots pine	19	34	58	1105	40°42'26"N 31°22'15"E
	Oriental beech	19	31	62	791	40°45'04"N 31°22'19"E

Detection of tree stem moisture

To determine the monthly stem MC, three identical trees and one tree were rotated monthly selected from each sampling plot. Cores were collected from the north-facing sides of the trunk (radial direction from bark to pith) at breast height using a Hagl f increment borer (Figure 1). Monthly diameter cores were taken sequentially from the above of the stem to the bottom of the breast height, as shown in Figure 2. Care was taken not to intersect the boreholes to prevent water transfer in the longitudinal direction of the body. All cores were removed from the drill, placed in zip-lock storage bags to prevent moisture loss in the field, and taken to the laboratory. On the same day, the fresh weights of the cores were measured in the laboratory with an accuracy of 0,001g. The radial sections of the core were then cut into six pieces, from the bark towards the core, and numbered (Figure 2).

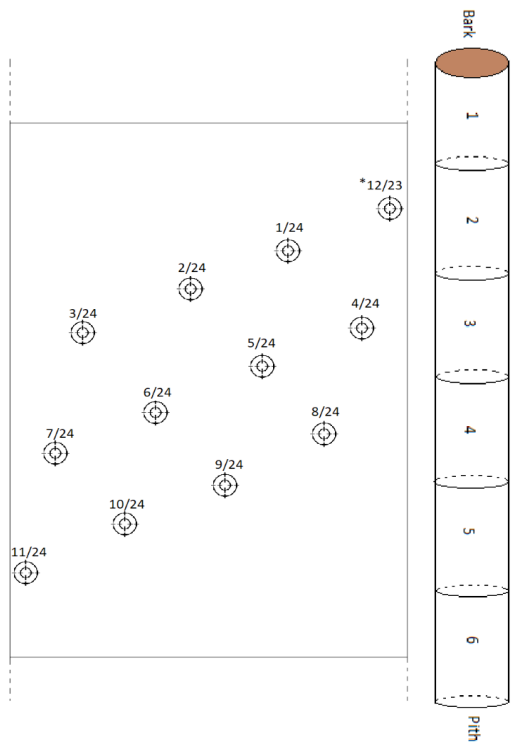


Figure 1: Plan of core sample cutting and illustration of the radial positions (*: Month/Year).

After weighing the wet weights (m_i) of the core samples, they were dried in an oven at 103 °C for 24 h, after which the oven-dry weights (m_0) were weighed again. The MC of each piece was obtained using Equation shown in Equation 1. This provided the MC of the heartwood and sapwood of each tree and the average monthly MC of the trunk.

$$MC = \frac{(m_i - m_0)}{m_0} \times 100 \text{ (\%)} \quad (1)$$

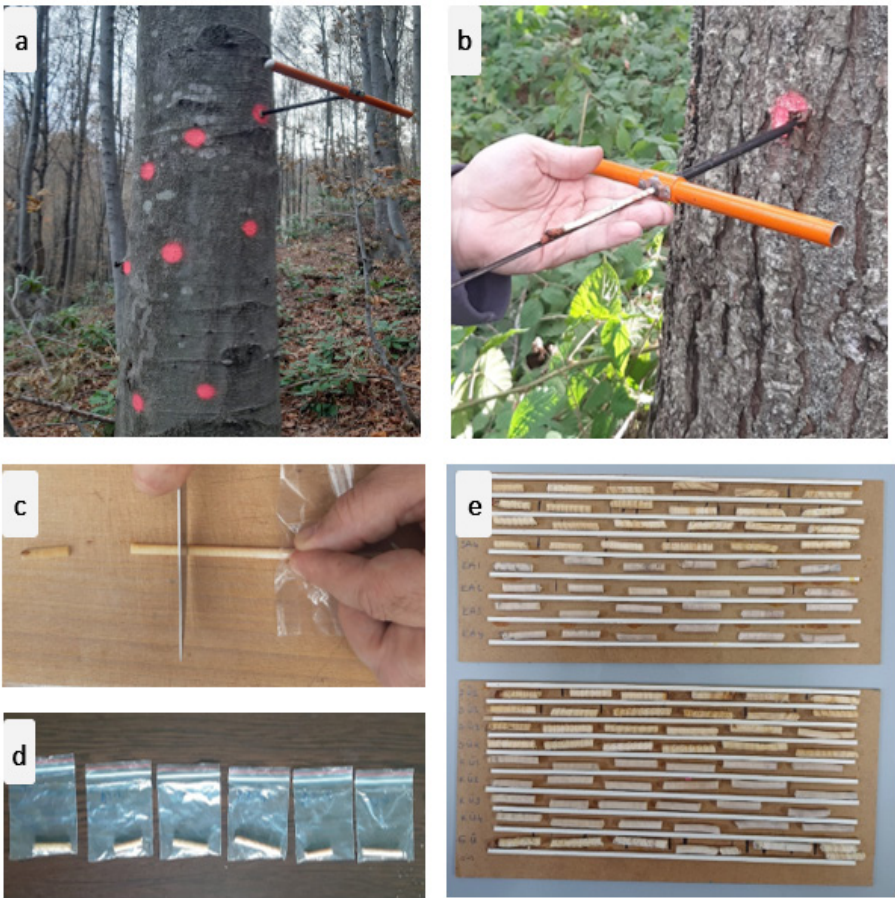


Figure 2: The process of obtaining core sample from trees.

Statistical analysis

A two-way analysis of variance (ANOVA) was performed for each tree species to determine the effect of altitude, time, and their interaction on stem moisture content (MC). Prior to analysis, stem MC data were subjected to an ArcSin transformation to meet the assumptions of normality. In each species × altitude group, four trees were sampled monthly: three trees were monitored repeatedly throughout the study, while the fourth sample was collected each month from a different individual. Given that a substantial portion of the observations originated from different individuals, the measurements were treated as independent, and a standard two-way ANOVA framework was applied. However, it is important to note that measurements from the same trees over time may be temporally dependent which was not fully addressed in this analysis and is a limitation. When ANOVA indicated significant differences, Tukey’s HSD test was performed for pairwise comparisons. To explore associations further, Pearson’s correlation analysis was used to examine relationships between stem MC and soil moisture, relative humidity, and air temperature. All statistical analyses were performed using IBM SPSS for Windows, version 21, and statistical significance was set at $p < 0.05$.

RESULT AND DISCUSSION

An inversely proportional relationship between air temperature and relative humidity was observed at different altitudes. The relative humidity was higher at higher altitudes than at lower altitudes. An opposite relationship was observed for relative humidity. The lowest mean air temperature and highest relative humidity were recorded in Feb. In general, high air temperatures and low relative humidity were observed in the 6th, 7th, and 8th months (Figure 3).

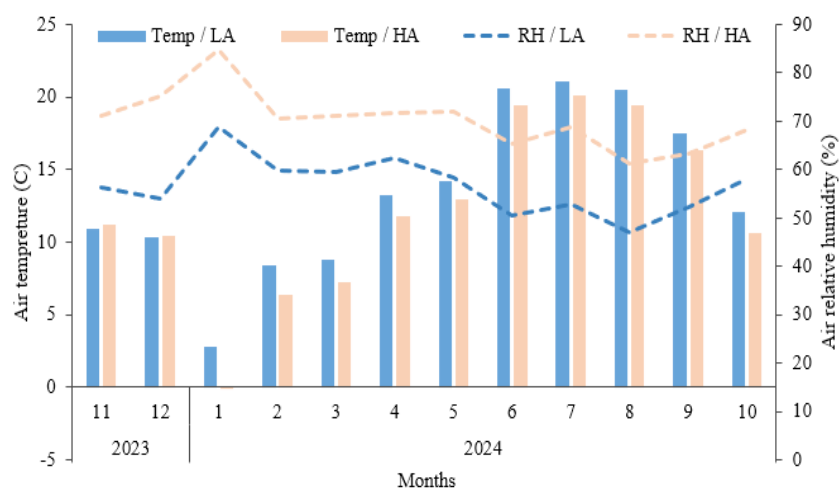


Figure 3: Monthly distribution of air temperature and relative humidity (RH) at different altitudes (LA, Low altitude; HA, High altitude).

The average soil moisture of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) soils at different depths at high and low altitudes (Figure 6) and their changes throughout the year are shown in (Figure 4, Figure 5). Soil moisture varied from month to month, and this variability was greater at lower altitudes. As expected, soil moisture was lowest in summer (6, 7, 8, and 9 months) and highest in Mar and May (38 % in scots pine (*Pinus sylvestris* L.) sites and 29 % in oriental beech (*Fagus orientalis* Lipsky) sites). Similar to our findings, Saryıldız and Savacı (2023) found that the soils of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) stands at higher altitudes (1189 m) were wetter than those at lower altitudes (871 m). This may be because evaporation from the soil is lower at high altitudes than at low altitudes owing to higher precipitation and lower air temperatures (Çepel 1995, Pellet and Hauck 2017). Soil moisture also increases with increasing soil depth (Kantarıcı 2000, Cao *et al.* 2023). During the summer months, the decrease in precipitation and increase in air temperature led to an increase in evaporation from the soil surface and tree leaf transpiration, resulting in more water being used from the soil and a decrease in soil moisture (Çepel 1995).

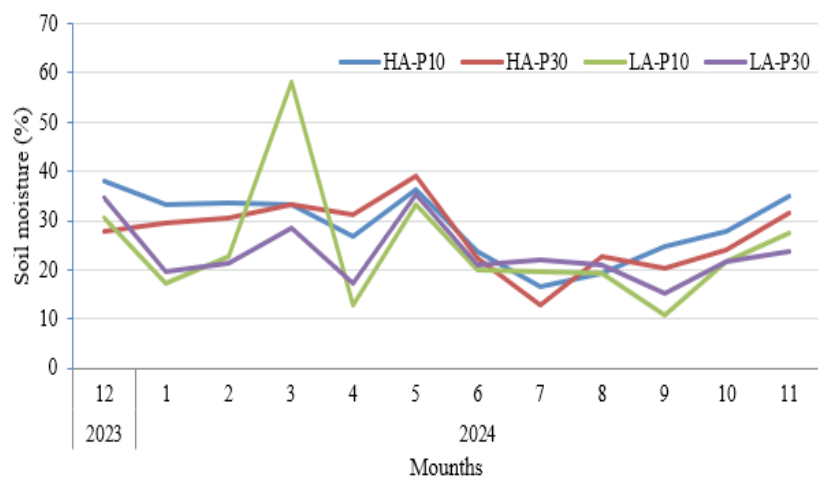


Figure 4: Monthly average soil moisture of scots pine (*Pinus sylvestris* L.) species at two different altitudes. LA, Low altitude; HA, High altitude; P10 (10 cm depth); P30 (30 cm depth)

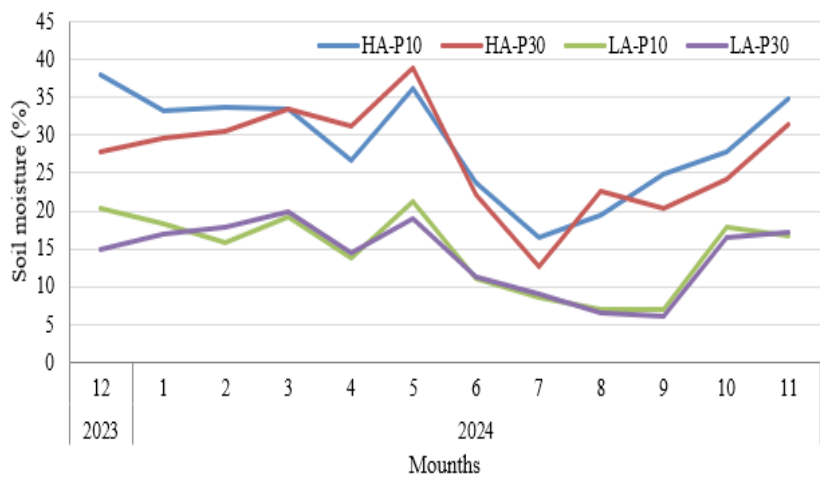


Figure 5: Monthly average soil moisture of oriental beech (*Fagus orientalis* Lipsky) species at two different altitudes. LA, Low altitude; HA, High altitude; P10 (10 cm depth); P30 (30 cm depth).

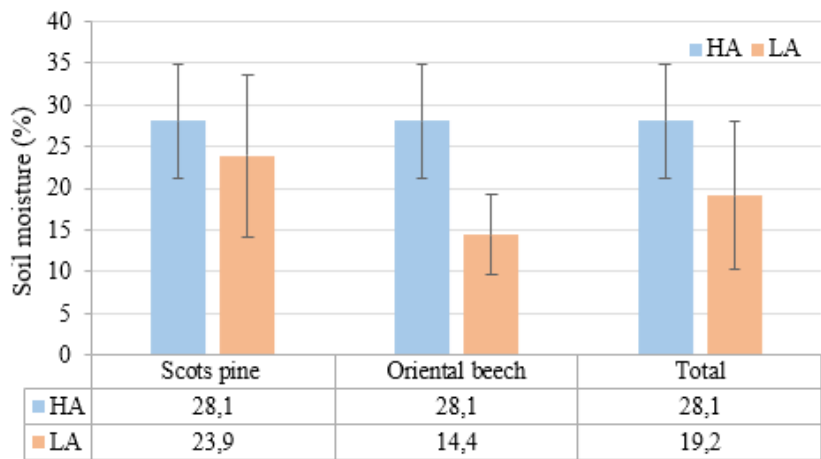


Figure 6: Changes in soil moisture with altitude differences in scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) forests.

The analysis of variance showed that altitude, time, and the interaction of altitude x time had a statistically significant effect on the stem MC of scots pine (*Pinus sylvestris* L.). Altitude and time affected the stem MC of oriental beech (*Fagus orientalis* Lipsky), but the interaction of altitude x time was not significant (Table 2).

Table 2: Analysis of variance results for stem MC (%) of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) tree.

Tree species / Factors		Type III Sum of Squares	df	Mean Square	F	Sig.
Scots pine (<i>Pinus sylvestris</i> L.)	Altitude (A)	0,214	1	0,214	17,913	0,000
	Time (T)	0,511	11	0,046	3,894	0,000
	Interaction (A×T)	0,290	11	0,026	2,211	0,023
	Error	0,860	72	0,012		
	Total	33,908	96			
	Corrected Total	1,876	95			
Oriental beech (<i>Fagus orientalis</i> Lipsky)	Altitude (A)	0,562	1	0,562	94,585	0,000
	Time (T)	0,316	11	0,029	4,844	0,000
	Interaction (A×T)	0,023	11	0,002	0,348	0,971
	Error	0,427	72	0,006		
	Total	48,931	96			
	Corrected Total	1,328	95			

When the changes in the monthly mean stem MC of the tree species were examined without considering the altitude difference, the annual mean stem MC of the tree species scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) were 54 % and 64 %, respectively (Table 3).

When the differences in altitude were considered, the stem MC of scots pine (*Pinus sylvestris* L.) was approximately 7 % higher and that of oriental beech (*Fagus orientalis* Lipsky) was approximately 13 % higher at higher altitudes than at lower altitudes. This is due to the fact that the difference between high and low altitudes is greater in scots pine (*Pinus sylvestris* L.) areas than in oriental beech (*Fagus orientalis* Lipsky) areas (Table 1). This altitudinal contrast is consistent with the cooler temperatures, lower atmospheric water demand and delayed soil-water depletion that elevation imposes on the growing season (Körner 2007), conditions that keep the xylem hydrated for longer into the year. The more pronounced response in oriental beech (*Fagus orientalis* Lipsky) can in turn be attributed to its diffuse-porous anatomy and poorly differentiated heartwood (Schweingruber 1990): because most of the stem cross-section functions as sapwood, changes in soil water availability translate more uniformly into stem MC than in scots pine (*Pinus sylvestris* L.), where the drier, resin-occluded heartwood damps the radial signal.

The mean stem MC of scots pine (*Pinus sylvestris* L.) was the lowest in Jan and Jun, with 47 % on an annual basis. The highest stem MC was 64 % in Feb. It is important to note that the transition from Jan to Feb was very sharp, from the lowest to the highest annual stem MC (Table 3). This situation can be attributed to the rapid transfer of frozen soil moisture to the stem with the melting of snow water and loosening of the soil in Feb. This abrupt rise is consistent with the snowmelt-driven stem rehydration documented in seasonally snow-covered conifer forests, where stored snow water becomes hydraulically available before transpiration resumes and contributes substantially to the recovery of internal stem-water reserves (Chan and Bowling 2017, Nehemy *et al.* 2022). The mid-summer minimum in June, by contrast, reflects the period of highest atmospheric demand, when transpiration draws on these reserves faster than soil supply can replace them.

When examining the stem MC of oriental beech (*Fagus orientalis* Lipsky) trees, a lower stem MC was found in the spring and summer months (Apr-Sep) compared to the monthly stem MC throughout the year. However, low values were observed in Jan. The highest stem MC was found in autumn (Oct to Dec) and Feb (Table 3). The lower stem MC observed between April and September overlaps with the leafed and physiologically active period of Oriental beech (*Fagus orientalis* Lipsky), when sustained transpiration progressively depletes internal water reserves; this pattern aligns with the well-documented sensitivity of *Fagus* species to soil-moisture deficits during the growing season (Köcher *et al.* 2009, Knüver *et al.* 2019). The autumn maximum reappears once leaf fall reduces canopy demand and soils begin to recharge, while the secondary February peak likely reflects the same snowmelt and soil-thaw window that governs the Scots pine (*Pinus sylvestris* L.) signal, although muted by the species’ deciduous habit.

Table 3: Changes in MC of scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) stems throughout the year (without any difference in altitude).

Months	Scots pine			Oriental beech		
	MC (%)		Std Error	MC (%)		Std Error
Dec	57,7	bcde	4,6	70,2	d	2,6
Jan	46,6	a	2,4	62,6	abc	3,0
Feb	64,1	e	6,6	71,1	d	3,2
Mar	60,0	cde	3,0	68,5	cd	2,5
Apr	49,1	ab	2,4	62,8	abc	2,8
May	57,5	bcde	3,5	61,1	a	2,8
Jun	46,8	a	2,5	59,2	a	3,2
Jul	51,2	abc	2,0	61,7	ab	1,8
Aug	50,4	abc	2,4	59,7	a	2,6
Sep	51,2	abc	2,9	59,2	a	3,1
Oct	52,3	abcd	2,2	68,1	cd	3,1
Nov	61,2	de	3,7	67,4	bcd	3,5
Total	54,0		1,1	64,3		0,9
High Altitude	57,7		1,7	70,0		1,0
Low Altitude	50,3		1,2	58,6		0,9

The variation in the stem MC of scots pine (*Pinus sylvestris* L.) with altitude and time is shown in Figure 7. In general, it can be seen that scots pine (*Pinus sylvestris* L.) at high altitudes have a higher stem MC throughout the year than those at lower altitudes. It can also be said that stem MC in winter and spring months is quite variable throughout the year. The most significant change was observed from Jan to Feb at high altitudes, when the average stem MC increased from 44 % to 79 %. The data on air temperature and relative humidity showed that, especially at high altitudes, the air temperature in Jan was very low (-1 °C), and in Feb, the average air temperature reached 7 °C. The effect of humidity in Jan was not obvious on stem MC because of the very low air temperature. However, when the air temperature increased in Feb, the MC of the scots pine (*Pinus sylvestris* L.) stem suddenly increased owing to the combined effect of air temperature and relative humidity.

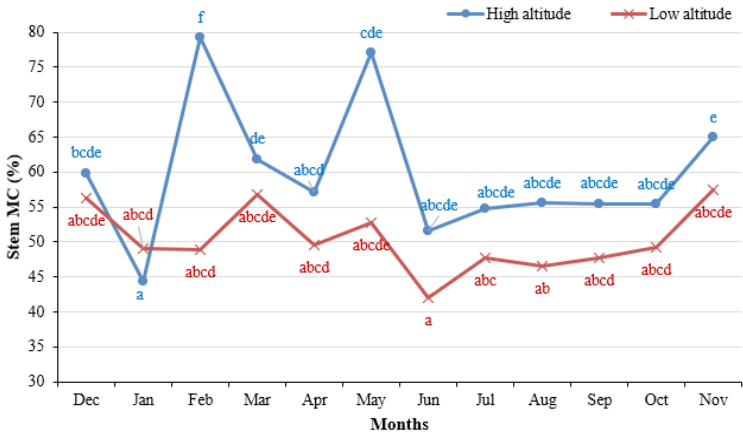


Figure 7: Variation of stem MC throughout the year in scots pine (*Pinus sylvestris* L.) trees at different altitudes.

The variation in the oriental beech (*Fagus orientalis* Lipsky) stem MC with altitude and time is shown in Figure 8. Beech trees at high altitudes have higher stem MC throughout the year than those at low altitudes. There was a significant change in stem MC between Jan and Feb. The lowest stem MC for oriental beech (*Fagus orientalis* Lipsky) trees grown at both altitudes was observed between April and Sep. However, it can be said that the stem MC of beech is higher in the winter and autumn months, except in Jan, than in the other seasons.

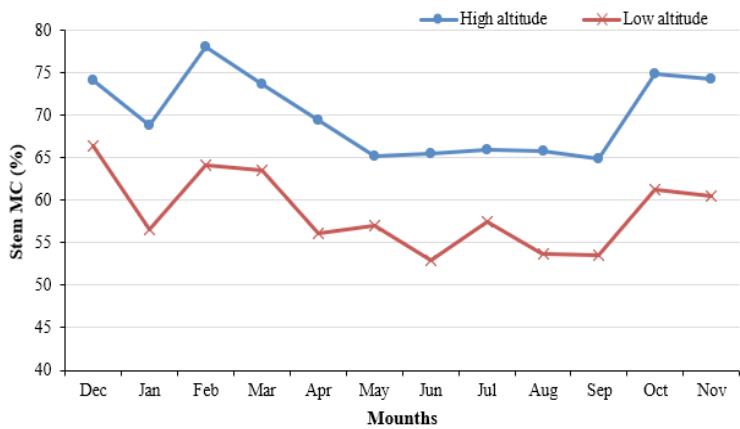


Figure 8: Variation of stem MC throughout the year in oriental beech (*Fagus orientalis* Lipsky) trees at different altitudes

There were strong positive correlations between stem MC and soil moisture in both scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky), but this correlation was higher in oriental beech (*Fagus orientalis* Lipsky) trees (Table 4). While the strength of the correlation between stem MC and soil moisture did not change with soil depth in scots pine (*Pinus sylvestris* L.) trees, it decreased with soil depth in oriental beech (*Fagus orientalis* Lipsky) trees. In other words, oriental beech (*Fagus orientalis* Lipsky) stem MC benefits more from topsoil moisture. This contrast reflects well-documented differences in rooting strategy between the two species: oriental beech (*Fagus orientalis* Lipsky), like its European congener *Fagus sylvatica*, maintains a fine-root system predominantly concentrated in the upper soil horizons (Finér *et al.* 2007, Leuschner 2020), whereas scots pine (*Pinus sylvestris* L.) develops a deeper, more vertically distributed root architecture that allows it to draw on subsoil water and decouples its uptake from short-term variations in the topsoil (Finér *et al.* 2007, Brinkmann *et al.* 2019). Therefore, the stronger topsoil dependence of oriental beech (*Fagus orientalis* Lipsky) provides a direct mechanistic link to the larger altitudinal contrast measured in its stem MC, because elevation prolongs the moist state of precisely that surface layer through cooler temperatures, longer-lasting snowpack, and reduced evaporative demand – a coupling that also identifies oriental beech (*Fagus orientalis* Lipsky) as the more climatically vulnerable of the two species under projected summer warming and earlier snowmelt. There was no relationship between stem MC and air relative humidity and air temperature in scots pine (*Pinus sylvestris* L.) trees, but there was a positive correlation between stem MC and relative humidity and a negative correlation with air temperature in oriental beech (*Fagus orientalis* Lipsky) trees (Table 4).

While scots pine (*Pinus sylvestris* L.) form taproots depending on soil depth, oriental beech (*Fagus orientalis* Lipsky) trees tend to form heart roots. Oriental beech (*Fagus orientalis* Lipsky) trees take up to 50 % of their soil water from the topsoil (Gessler *et al.* 2022), and they struggle to compensate by accessing deeper soil water during summer drought (Lüttschwager and Jochheim 2020, Magh *et al.* 2020, Gessler *et al.* 2022). However, scots pine (*Pinus sylvestris* L.) can benefit from water in deeper soil layers than oriental beech (*Fagus orientalis* Lipsky) because of its deep taproots (Bishop and Dambrine 1995). Therefore, in our study, while the relationship between soil moisture and stem MC at both depths was the same in scots pine (*Pinus sylvestris* L.), the relationship between topsoil moisture and stem MC was much stronger in oriental beech (*Fagus orientalis* Lipsky) trees.

Table 4: Correlations between scots pine (*Pinus sylvestris* L.) and beech (*Fagus orientalis* Lipsky) stem moisture content (MC), soil moisture, air relative humidity and temperature.

	Mean Soil moisture (%)	Soil moisture (10cm depth)	Soil moisture (30cm depth)	Air Relative Humidity (%)	Air Temperature
Scots pine (<i>Pinus sylvestris</i> L.) stem MC	0,530	0,497	0,486	0,364	-0,288
Sig.	0,008	0,014	0,016	0,080	0,172
Beech stem MC	0,829	0,851	0,780	0,723	-0,448
Sig.	0,000	0,000	0,000	0,000	0,028

The average moisture change of the tree species along the cross-section (radius) during the year is shown in Figure 9. For Scots pine (*Pinus sylvestris* L.), the highest moisture content of the cross-section was observed in the 2nd and 3rd pieces (between 4-7 cm) from the bark section at both altitudes. A sharp decrease in the MC was observed as it approached the core. This observation suggests that moisture variations may exist within the sapwood and heartwood in the radial direction of the wood. Similar results have been reported in previous studies (Constant *et al.* 2002). No sharp change was detected across the cross-section of oriental beech (*Fagus orientalis* Lipsky) trees, unlike in Scots pine (*Pinus sylvestris* L.) (Figure 9c, Figure 9d). This is because species belonging to the oriental beech (*Fagus orientalis* Lipsky) genus generally do not have a distinct heartwood-sapwood boundary, and their trunks are predominantly composed of sapwood (Wagenführ 1980, Ross 2010). It can be said that this anatomical characteristic leads to a relatively more homogeneous radial moisture content distribution compared to species with a clear distinction between heartwood and sapwood. In addition, the size, width, and structure of the ray parenchyma can affect transverse water transport. The fact that beech species have wider wood rays than Scots pine (*Pinus sylvestris* L.) also influences radial water transport and, as a result, leads to a more homogeneous water distribution (Carlquist 2001). In both scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky), the outer sapwood has a higher MC ratio than the inner sapwood, and similarly, the outer heartwood has a higher MC ratio than the inner heartwood.

The MC in the cross-section ranged from 85 % to 36 % at high altitudes and from 68 % to 35 % at low altitudes. In a previous study, MC was investigated at three different positions in the radial direction of another beech species, common beech, and MC ratios of 48 %, 74 %, and 81 % were determined from the inside to the outside, respectively (Longuetaud *et al.* 2017). In general, the sapwood of conifers has a higher MC than the heartwood (Tsoumis 1991, Haygreen and Bowyer 1996, Chiu and Lin 2007). This phenomenon can be attributed to the passage aspiration that occurs in the passages during heartwood formation, the fact that sapwood continues to conduct water in the tree stem, unlike heartwood, and the fact that the cells that previously served as conduits in heartwood are filled with various extractives (Koch 1972, Panshin and De Zeeuw 1980, Tsoumis 1991).

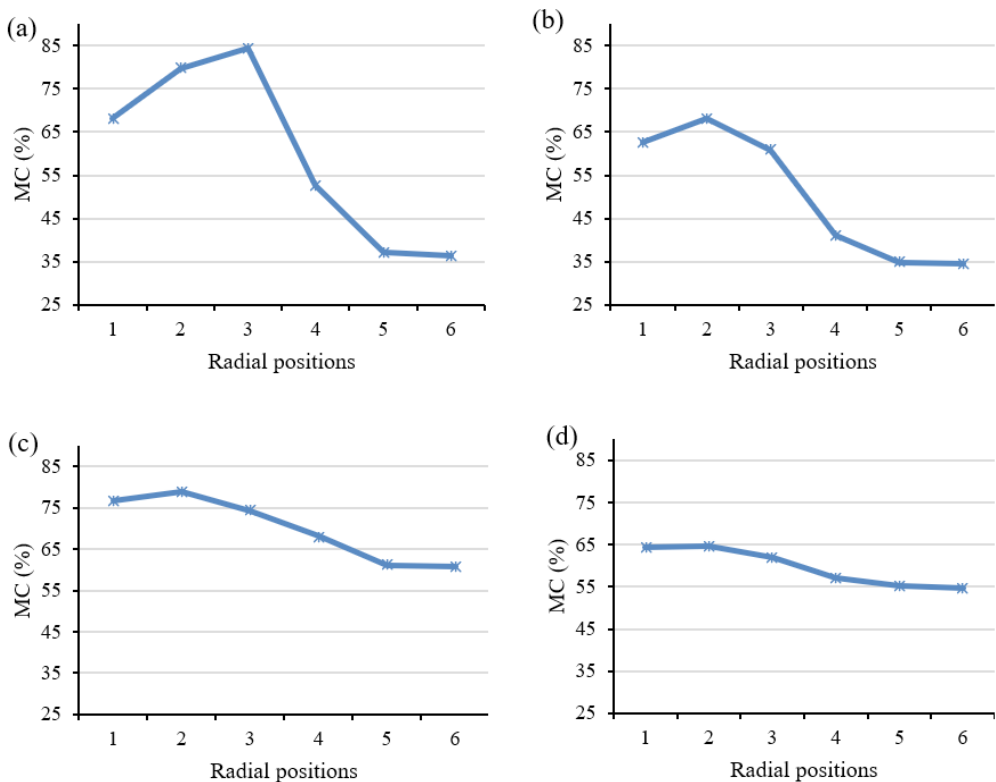


Figure 9: The radial profile of stem MC in Scots pine (*Pinus sylvestris* L.) and oriental beech (*Fagus orientalis* Lipsky) trees. (a: Scots pine (*Pinus sylvestris* L.)), HA; b: Scots pine (*Pinus sylvestris* L.), LA; c: Oriental beech (*Fagus orientalis* Lipsky), HA; d: Oriental beech (*Fagus orientalis* Lipsky), LA).

The monthly variation in heartwood and sapwood MC throughout the year shows that the difference between heartwood and sapwood MC does not change at both the lower and upper altitudes, although it does vary according to the month (Figure 10). As the MC increased in the heartwood and decreased in the sapwood, especially between the 7th and 11th months, it can be said that the MC difference increased in these months (Figure 10). In general, studies have shown that the MC in the sapwood of conifers is significantly higher than that in the heartwood (Bamber and Fukazawa 1985, Kravka *et al.* 1999). Previous studies have found that sapwood MC varies throughout the year (Chalk and Bigg 1956), and that this variation can occur on a daily basis (Waring and Running 1978). As shown in Figure 10, there is a difference of 2 and 2,5 times between the average MC of the sapwood and heartwood of scots pine (*Pinus sylvestris* L.) (*Pinus sylvestris* L.), with the sapwood having a higher MC. This situation is similar to that reported by Kravka *et al.* (1999), who found that the difference between the average MC of scots pine (*Pinus sylvestris* L.) (*Pinus sylvestris* L.) sapwood and heartwood was approximately two times.

As shown in Figure 10, although the difference in altitude significantly affects the sapwood MC (upper-altitude average MC 80 %, lower-altitude average MC 65 %), it does not significantly affect the average MC of the heartwood (upper-altitude average MC 34 %, lower-altitude average MC 36 %).

The variation in MC along the cross-section for oriental beech (*Fagus orientalis* Lipsky) was not as significant as that for scots pine (*Pinus sylvestris* L.). The average MC along the cross-section varies between 79-61 % at the upper altitude and 64-54 % at the lower altitude. The highest MC along the cross-section was found in the 2nd and 3rd parts (between 4-9 cm), and the MC gradually decreased as it approached the core. This decrease is due to the effect of soil formation, which occurs in hardwood species together with the formation of heartwood (Ward 1986).

In general, when comparing the sapwood and heartwood of tree species in terms of MC, it was found that the MC difference between sapwood and heartwood was higher in scots pine (*Pinus sylvestris* L.). Previous studies have also shown that conifers generally have greater MC differences than hardwoods (Fromm *et al.* 2001, Gartner *et al.* 2004). Although water transport in the trunk occurs in the sapwood, which is the outermost part, the heartwood parts of scattered-path woods, especially oriental beech (*Fagus orientalis* Lipsky), have also been found to play a role in transport, resulting in a high MC in the heartwood of these species (Gebauer *et al.* 2008, Longuetaud *et al.* 2017).

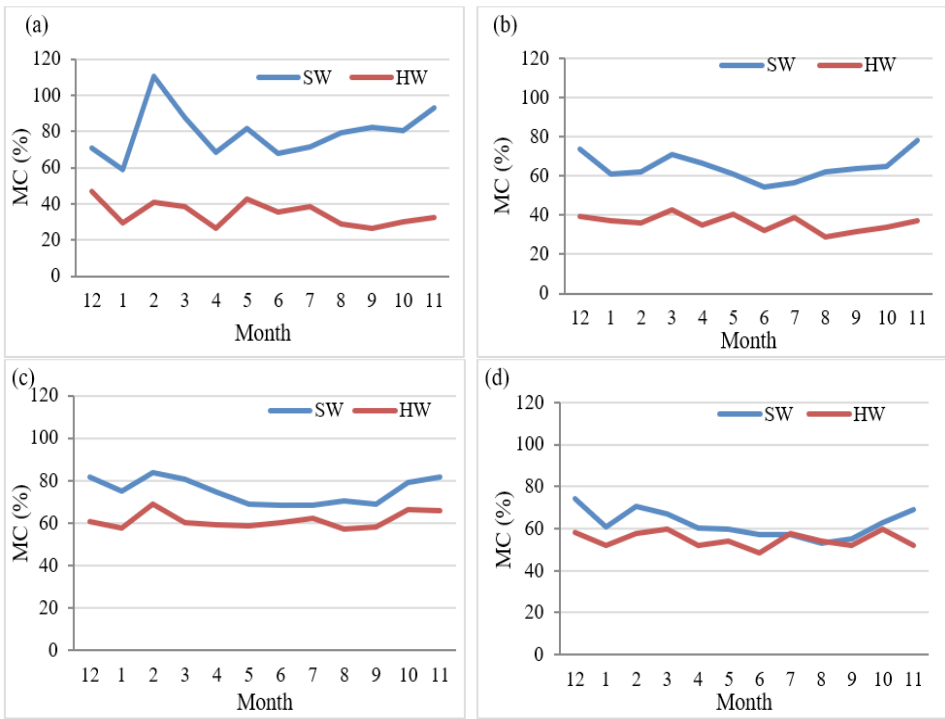


Figure 10: Variation of MC in sapwood and heartwood along the year. (a: Scots pine (*Pinus sylvestris* L.), HA; b: Scots pine (*Pinus sylvestris* L.), LA; c: Oriental beech (*Fagus orientalis* Lipsky), HA; d: Oriental beech (*Fagus orientalis* Lipsky), LA).

CONCLUSIONS

The effects of altitude and time on stem moisture content (MC) were significant in both Scots pine (*Pinus sylvestris* L.) and Oriental beech (*Fagus orientalis* Lipsky). In Scots pine, the annual mean stem MC was 57% at high altitudes and 50% at low altitudes. Monthly stem MC varied throughout the year and was lower in January, April, and June–October than in the remaining months. Stem MC showed a strong positive correlation with soil moisture, whereas no significant relationship was found with air temperature or relative humidity. Along the radial profile, MC increased from the outer to the inner sapwood, reaching an average of approximately 85%, and then decreased sharply to approximately 35% in the heartwood. The difference between sapwood and heartwood MC remained evident throughout the year and increased with altitude.

In Oriental beech, the annual mean stem MC was 70% at high altitudes and 58% at low altitudes. Monthly stem MC also varied throughout the year and was lower in January and from April to September than in the remaining months. Stem MC was positively correlated with soil moisture and relative humidity and negatively correlated with air temperature. Along the radial profile, MC increased slightly from the outer to the inner sapwood, reaching an average of approximately 79%, and then gradually decreased to approximately 55% in the heartwood. The difference between sapwood and heartwood MC was smaller than that observed in Scots pine and disappeared at lower altitudes during July and October.

The moisture content of logs produced from high-altitude forests was higher than that of logs from low-altitude forests. In both species, stem MC was lower during the summer months. Log MC varied according to species, season, altitude, and radial position within the stem. Seasonal changes in stem moisture content provide information that may contribute to forest fire risk assessment, analysis of tree physiology and drought stress, optimization of wood drying and preservation processes, and estimation of biomass energy yield.

Author contributions

YS: Conceptualization, field studies, sampling and testing, writing-original draft preparation and editing. MY: Conceptualization, methodology, Field studies, sampling and testing, writing-original draft preparation and editing. AKÖ: Conceptualization, methodology, field studies, sampling and testing, statistical analysis, writing-original draft preparation and editing.

Conflict interest

The authors declare no conflicts of interest.

REFERENCES

- Bamber, R.; Fukazawa, K. 1985.** Sapwood and heartwood: a review. *Forest Products Abstracts* 8(9): 265–278. <https://www.cabidigitallibrary.org/doi/pdf/10.5555/19870616672>
- Brinkmann, N.; Eugster, W.; Buchmann, N.; Kahmen, A. 2019.** Species-specific differences in water uptake depth of mature temperate trees vary with water availability in the soil. *Plant Biology* 21(1): 71–81. <https://doi.org/10.1111/plb.12907>
- Bishop, K.; Dambrine, E. 1995.** Localization of tree water uptake in Scots pine (*Pinus sylvestris* L.) and Norway spruce with hydrological tracers. *Canadian Journal of Forest Research* 25(2): 286–297. <https://doi.org/10.1139/x95-033>
- Cao, J.; Chen, Y.; Jiang, Y.; Chen, J.; Zhang, Y.; Wu, J. 2023.** Different responses of soil moisture to different artificial forest species on the Loess Plateau. *Sustainability* 15(19): 14275. <https://doi.org/10.3390/su151914275>
- Carlquist, S. 2001.** Comparative Wood Anatomy: Systematic, Ecological, and Evolutionary Aspects of Dicotyledon Wood. Springer Berlin Heidelberg. ISBN:3540411739, <https://link.springer.com/book/10.1007/978-3-662-04578-7>
- Chalk, L.; Bigg, J.M. 1956.** The distribution of moisture in the living stem in Sitka spruce and Douglas fir. *Forestry* 29(1): 5–21. <https://doi.org/10.1093/forestry/29.1.5>

Chan, A. M.; Bowling, D. R. 2017. Assessing the thermal dissipation sap flux density method for monitoring cold season water transport in seasonally snow-covered forests. *Tree Physiology* 37(7): 984-995. <https://doi.org/10.1093/treephys/tpx049>

Chen, Y.; Huang, Y.; Chen, S. 1998. A study on moisture distribution of green wood and variations of specific gravity in *Cryptomeria japonica* D. Don. *Taiwan Journal of Forest Science* 13(2): 91-100.

Chiu, C.M.; Lin, C.J. 2007. Radial distribution patterns of the green moisture content in trunks of 46-year-old red cypress (*Chamaecyparis formosensis*). *Journal of Wood Science* 53(5): 374-380. <https://doi.org/10.1007/s10086-007-0885-9>

Constant, T.; Nepveu, G.; Huber, F. 2002. Intra- and inter-tree variability of moisture content in standing sessile oak (*Quercus petraea* Liebl.). *Holzforschung* 56(2): 117-124. <https://doi.org/10.1515/HF.2002.020>

Çepel, N. 1995. *Forest Ecology*. 4th ed. IU Faculty of Forestry: Istanbul, Türkiye. 536 p. ISBN:975-404-398-1.

Finér, L.; Helmisaari, H. S.; Lohmus, K.; Majdi, H.; Brunner, I.; Børja, I.; Eldhuset, T.; Godbold, D.; Grebenc, T.; Konôpka, B.; Kragher, H.; Möttönen, M. R.; Ohashi, M.; Oleksyn, J.; Ostonen, I.; Uri, V.; Vanguelova, E. 2007. Variation in fine root biomass of three European tree species: Beech (*Fagus sylvatica* L.), Norway spruce (*Picea abies* L. Karst.), and Scots pine (*Pinus sylvestris* L.) (*Pinus sylvestris* L.). *Plant Biosystems* 141(3): 394-405. <https://doi.org/10.1080/11263500701625897>

Fromm, J.H.; Sautter, I.; Matthies, D.; Kremer, J.; Schumacher, P.; Ganter, C. 2001. Xylem water content and wood density in spruce and oak trees detected by high-resolution computed tomography. *Plant Physiology* 127(2): 416-425. <https://doi.org/10.1104/pp.010194>

Gartner, B.L.; Moore, J.R.; Gardiner, B.A. 2004. Gas in stems: abundance and potential consequences for tree biomechanics. *Tree Physiology* 24(11): 1239-1250. <https://doi.org/10.1093/treephys/24.11.1239>

Gebauer, T.; Horna, V.; Leuschner, C. 2008. Variability in radial sap flux density patterns and sapwood area among seven co-occurring temperate broad-leaved tree species. *Tree Physiology* 28(12): 1821-1830. <https://doi.org/10.1093/treephys/28.12.1821>

GDM. 2024. Provincial Statistics of the General Directorate of Meteorology. General Directorate of Meteorology: Ankara, Türkiye. <https://mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?k=A&m=-DUZCE>

GDF. 2024. *Official Forestry Statistics*. Ministry of Agriculture and Forestry, General Directorate of Forestry: Ankara, Türkiye. <https://www.ogm.gov.tr/tr/e-kutuphane/resmi-istatistikler>

Gessler, A.; Bächli, L.; Rouholahnejad Freund, E.; Treydte, K.; Schaub, M.; Haeni, M.; Weiler, M.; Seeger, S.; Marshall, J.; Hug, C.; Zweifel, R.; Hagedorn, F.; Rigling, A.; Saurer, M.; Meusburger, K. 2022. Drought reduces water uptake in beech from the drying topsoil, but no compensatory uptake occurs from deeper soil layers. *New Phytologist* 233(1): 194-206. <https://doi.org/10.1111/nph.17767>

Haygreen, J.; Bowyer, J. 1996. *Forest Products and Wood Science: An Introduction*. 3rd ed. Iowa State University Press: Ames, Iowa, USA. 484 p. ISBN:978-0-8138-2256-3

Kantarci, M.D. 2000. *Soil Science*. 2nd ed. İstanbul University Forestry Faculty Press: İstanbul, Türkiye. 420 p. ISBN:975-404-588-7

Kayacık, H. 1980. *The Special Systematic of Forestry and Park Trees*. University of Istanbul, Faculty of Forestry Press: Istanbul, Türkiye.

Koch, P. 1972. *Utilization of the Southern Pines*. U.S. Southern Forest Experiment Station. Agriculture Handbook No.420. US Government Printing Office. Washington, USA. 1619 p.

Köcher, P.; Gebauer, T.; Horna, V.; Leuschner, C. 2009. Leaf water status and stem xylem flux in relation to soil drought in five temperate broad-leaved tree species with contrasting water use strategies. *Annals of Forest Science* 66: 101. <https://doi.org/10.1051/forest/2008076>

- Körner, C.** 2007. The use of 'altitude' in ecological research. *Trends in Ecology & Evolution* 22(11): 569–574. <https://doi.org/10.1016/j.tree.2007.09.006>
- Kravka, M.; Krejzar, T.; Čermák, J.** 1999. Water content in stem wood of large pine and spruce trees in natural forests in central Sweden. *Agricultural and Forest Meteorology* 98–99: 555–562. [https://doi.org/10.1016/S0168-1923\(99\)00123-9](https://doi.org/10.1016/S0168-1923(99)00123-9)
- Knüver, T.; Bär, A.; Ganthaler, A.; Gebhardt, T.; Grams, T. E. E.; Häberle, K. H.; Hesse, B. D.; Losso, A.; Tomedi, I.; Mayr, S.; Beikircher, B.** 2022. Recovery after long-term summer drought: Hydraulic measurements reveal legacy effects in trunks of *Picea abies* but not in *Fagus sylvatica*. *Plant Biology* 24(7): 1240–1253. <https://doi.org/10.1111/plb.13444>
- Leuschner, C.** 2020. Drought response of European beech (*Fagus sylvatica* L.)—A review. *Perspectives in Plant Ecology, Evolution and Systematics* 47: 125576. <https://doi.org/10.1016/j.ppees.2020.125576>
- Longuetaud, F.; Mothe, F.; Santenoise, P.; Diop, N.; Dlouha, J.; Fournier, M.; Deleuze, C.** 2017. Patterns of within-stem variations in wood specific gravity and water content for five temperate tree species. *Annals of Forest Science* 74(3). e64. <https://doi.org/10.1007/s13595-017-0657-7>
- Lüttschwager, D.; Jochheim, H.** 2020. Drought primarily reduces canopy transpiration of exposed beech trees and decreases the share of water uptake from deeper soil layers. *Forests* 11(5): 537. <https://doi.org/10.3390/f11050537>
- Magh, R.K.; Eiferle, C.; Burzlaff, T.; Dannenmann, M.; Rennenberg, H.; Dubbert, M.** 2020. Competition for water rather than facilitation in mixed beech-fir forests after drying-wetting cycle. *Journal of Hydrology* 587: 124944. <https://doi.org/10.1016/j.jhydrol.2020.124944>
- Matheny, A.M.; Bohrer, G.; Garrity, S.R.; Morin, T.H.; Howard, C.J.; Vogel, C.S.** 2015. Observations of stem water storage in trees of opposing hydraulic strategies. *Ecosphere* 6(9): 165. <https://doi.org/10.1890/ES15-00170.1>
- Mátyás, C.; Ackzell, L.; Samuel, C.** 2004. *EUFORGEN Technical Guidelines for Genetic Conservation and Use for Scots pine (Pinus sylvestris L.) (Pinus sylvestris)*. International Plant Genetic Resources Institute: Rome, Italy. 6 p. ISBN: 92-9043-661-1
- Nakada, R.; Fujisawa, Y.; Hirakawa, Y.** 1999a. Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D. Don II: Types found in wet-area distribution patterns in transverse sections of the stem. *Journal of Wood Science* 45(3): 194–199. <https://doi.org/10.1007/BF01177725>
- Nakada, R.; Fujisawa, Y.; Hirakawa, Y.** 1999b. Soft X-ray observation of water distribution in the stem of *Cryptomeria japonica* D. Don I: General description of water distribution. *Journal of Wood Science* 45(3): 188–193. <https://doi.org/10.1007/BF01177724>
- Nehemy, M. E.; Maillet, J.; Perron, N.; Pappas, C.; Sonnentag, O.; Baltzer, J. L.; Laroque, C. P.; McDonnell, J. J.** 2022. Snowmelt water use at transpiration onset: Phenology, isotope tracing, and tree water transit time. *Water Resources Research* 58(9): e2022WR032344. <https://doi.org/10.1029/2022WR032344>
- Oberhuber, W.; Gruber, A.; Wieser, G.** 2023. Seasonal and daily xylem radius variations in scots pine (*Pinus sylvestris* L.) are closely linked to environmental factors affecting transpiration. *Biology* 12(9): 1251. <https://doi.org/10.3390/biology12091251>
- Pacheco, A.; Camarero, J.J.; Ribas, M.; Gazol, A.; Gutierrez, E.; Carrer, M.** 2018. Disentangling the climate-driven bimodal growth pattern in coastal and continental Mediterranean pine stands. *Science of the Total Environment* 615: 1518–1526. <https://doi.org/10.1016/j.scitotenv.2017.09.133>
- Panshin, A.J.; De Zeeuw, C.** 1980. *Textbook of Wood Technology: Structure, Identification, Properties, and Uses of the Commercial Woods of the United States and Canada*. 4th ed. McGraw-Hill: New York, USA. 772 p. ISBN: 978-0-07-048441-2

Pellet, C.; Hauck, C. 2017. Monitoring soil moisture from middle to high elevation in Switzerland: set-up and first results from the SOMOMOUNT network. *Hydrology and Earth System Sciences* 21(6): 3199–3220. <https://doi.org/10.5194/hess-21-3199-2017>

Ross, R. J. 2010. *Wood handbook: Wood as an engineering material*. General Technical Report FPL-GTR-190. USDA Forest Service: Madison, Wisconsin, USA. 509 p. <http://dx.doi.org/10.2737/FPL-GTR-190>

Sarıyıldız, T.; Savacı, G. 2023. Variation in soil properties and nutrient stocks under different forest tree species with altitude, aspect and soil depths. *Journal of Bartın Faculty of Forestry* 25(2): 279–294. <https://doi.org/10.24011/barofd.1256500>

Schweingruber, F.H. 1990. *Anatomy of European Woods*. Verlag Paul Haupt: Bern, Switzerland. 800 p. ISBN:978-3-258-04258-9

Song, X.; Li, J.; Zhang, W.; Tang, Y.; Sun, Z.; Cao, M. 2016. Variant responses of tree seedling to seasonal drought stress along an elevational transect in tropical montane forests. *Scientific Reports* 6(1): 36438. <https://doi.org/10.1038/srep36438>

Tsoumis, G. 1991. *Science and Technology of Wood: Structure, Properties, Utilization*. Van Nostrand Reinhold: New York, USA. 491 p. ISBN: 978-3-941300-22-4

Wagenführ, R. 1980. *Wood anatomy with special reference to wood technology*. 2nd ed. VEB Fachbuchverlag: Leipzig, Germany. 328 p.

Ward, J.C. 1986. The effect of wetwood on lumber drying times and rates: an exploratory evaluation with longitudinal gas permeability. *Wood and Fiber Science* 18(2): 288–307. <https://wfs.swst.org/index.php/wfs/article/view/1208>

Ward, J.C.; Pong, W. 1980. *Wetwood in Trees: A Timber Resource Problem*. General Technical Report PNW-GTR-112. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 59 p. <https://doi.org/10.2737/PNW-GTR-112>

Waring, R.H.; Running, S.W. 1978. Sapwood water storage: its contribution to transpiration and effect upon water conductance through the stems of old-growth Douglas-fir. *Plant, Cell and Environment* 1(2): 131–140. <https://doi.org/10.1111/j.1365-3040.1978.tb00754.x>

Yaltırık, F. 1982. *Fagus L.* In: P.H. Davis (ed.), *Flora of Turkey and the East Aegean Islands*, Vol. 7, Edinburgh: Edinburgh University Press, pp. 657–658. 947 p. ISBN: 0-85224-396-0.