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ORIGINAL PAPER

Occurrence and characteristics of frost ribs in sessile oak stands

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ABSTRACT

Frost ribs (frost cracks) are common wood defects in oak stands. Tree trunks with frost ribs cannot be used as high-quality industrial wood. Considering the great economic importance of oak for forest management, the objectives of this study were to determine the proportion of trees with frost ribs in the stand, to characterize frost ribs, to compare selected morphological characteristics of trees with and without frost ribs, and to compare the basic density of wood and moisture content (in winter) of trees with and without frost ribs. We estimated that in oak stands, the proportion of trees with frost ribs was about 6.5%. We found that trees with frost ribs have statistically significantly higher moisture content in winter than trees without frost ribs. The analysis indicated that the taller trees, characterized by shorter the frost ribs. We found no differences in breast height diameter, height or crown length between trees with and without frost ribs. For this reason, it is not possible to formulate guidelines for silviculture based on morphological characteristics that might be used to identify trees with higher sensitivity to low temperatures.

KEY WORDS

basic density, frost cracking, frost cracks, moisture content, tree morphology, *Quercus petraea*

Introduction

Oak wood is characterized by high density and strength. It also contains a high proportion of heartwood, and numerous medullary rays. The oak heartwood has a high moisture content, unlike to the heartwood of softwood (Kravka *et al.*, 1999; Nakada, 2006; Longuetaud *et al.*, 2016; Tomczak *et al.*, 2022a). In the past, oak wood was mainly used in construction and boatbuilding. At present oak wood is very valuable and most often is used to make furniture, floors, doors, stairs, and veneers.

In Poland oak is very important in forest management. Oak stands have the largest area among deciduous stands (7.9%) and second overall, after pine stands (58.0%) (Statistics Poland, 2021). Frost ribs (frost cracks) are common wood defects in oak stands. Through the crack, the tree can be attacked by wood-degrading fungi. As a result, the quality and value of the wood

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significantly decreases (Mania and Tomczak, 2020). Tree trunks with frost ribs cannot be used as high-quality industrial wood.

Frost cracks are most common in hardwood, and less common in soft hardwood or softwood (Hart and Dennis, 1971; Sakai and Larcher, 1987; Persson, 1994; Kula *et al.*, 2006; Burton *et al.*, 2008; Viherä-Aarnio and Velling, 2017). Frost cracks often occur in oak trees (Kubler, 1988). However, this depends on the species of oak or its origin (Savill *et al.*, 1993; Danielewicz *et al.*, 2014; Câmpu and Dumitrache, 2015). Sessile oak *Q. petraea* (Matt.) Liebl. and common oak *Q. robur* L., which are northern species, are less susceptible to freezing than Turkey oak *Q. cerris* L. and Hungarian oak *Q. frainetto* Ten., which are southern species (Mattheck and Kubler, 1997). Danielewicz *et al.* (2014) found a very high proportion of damaged trees in Polish stands of Turkey oak *Q. cerris*, which is native to Southern Europe. Similar results were reported in the case of birch (Viherä-Aarnio and Velling, 2017). The frequency and severity of frost cracking is higher near the northern limits of the species' range (Lamprecht, 1950), leading to the general assumption that frost cracking is inevitable in northern latitudes (Butin and Shigo, 1981; Sakai and Larcher, 1987).

A theory of Hartig *et al.* from the late 19th century explains that frost cracks are mainly moisture-related, not thermal (Ishida, 1963). Mayer-Wegelin *et al.* (1962) also consider it unlikely that temperature differences in the trunk wood contribute to the development of frost cracks. This is confirmed by the observations of Dziurzyński (2005), which show that the width of a frost crack in an oak tree may be much greater than calculations based on the coefficient of thermal expansion across the wood fibers would indicate.

The mechanism of frost cracking was initially explained by thermal shrinkage of the outer layers of wood due to low-temperature conductivity (Godlewski, 1981; Kubler, 1987). The cold outer wood of stems tends to shrink under frost faster than the relatively warm inner wood, and undergoes tangential stress. To obtain an estimate of the effect of temperature gradients, Kubler (1987) considered a hypothetical trunk in which the temperature of a narrow ring of sapwood drops to a very low level, while the entire heartwood is still at freezing point and the ring of sapwood compresses the heartwood. In actual frost-exposed trunks, the sapwood temperature remains above the air temperature as long as heat flows from the interior of the wood to the surface of the trunk. Later, when almost all of the moisture in the wood has frozen and the frost front approaches the center of the trunk, almost all of the wood is very cold and in a state of frost shrinkage so that it only slightly limits the tangential shrinkage of the outer wood. The tangential deformation caused by the actual temperature gradient is about half of the frost shrinkage value of small samples at sapwood temperature. Therefore, temperature gradients are important factors in the formation of frost cracks, but not as important as the anisotropy of frost shrinkage (Kubler, 1983, 1987).

In nature, where the temperature drop is generally slow, ice usually forms in the intercellular spaces between the cell wall and the protoplast. Thus, among other things, extracellular crystallization of water occurs. The water vapor pressure in the spaces above the ice decreases, and a water potential gradient is formed between the unfrozen interior of the cell and the extracellular environment. The process leads to dehydration and shrinkage of the cell. The lower the ambient temperature, the later equilibrium is reached between the water potential over the ice and in the cells, and thus the greater are the effects of cell dehydration (Kacperska, 2002). Shrinkage caused by 'internal drying' similarly to normal wood shrinkage is much greater in the direction of the annual rings than in the direction of the medullary rays. As a result of the difference in tangential and radial shrinkage, critical transverse tensile stresses occur at low trunk temperatures, leading to frost cracks (Mayer-Wegelin *et al*., 1962). Drought cracks develop in an identical manner. Drought cracks are initiated by tangential stresses as a result of sapwood drying and shrinking in response to water deficit (Cameron *et al*., 2017). Mattheck and Kubler (1997) also add that the maximum tangential stress is strongly correlated with the size and number of medullary rays.

Frost cracks are irreversible structural disorders, as they lead to radial-longitudinal splitting of tree trunks. The size and location of frost cracks vary from tree to tree. Frost cracks penetrate deep into the core of the tree. When frost cracks close, callus tissues of wood and bark bridge the crack. In the following winter, however, the crack may reopen. As a rule, cracking and healing are repeated over several years, and frost ribs develop (Kubler, 1987).

The frost cracks does not occur on all trees; it may affect only a part of the population (Sakai and Larcher, 1987; Sano and Fukazawa, 1996). The phenomenon may be related to individual characteristics of a tree. Frost cracks become sites of increased penetration into the wood by various types of decay fungi (Schmidt, 2006; Čakšs *et al*., 2022). Mania and Tomczak (2020) compared selected physical and mechanical properties of oak wood with and without frost ribs. The wood of trees with frost ribs exhibited higher density and lower mechanical strength. This is of particular importance because the samples tested had no discoloration or other symptoms indicative of rot.

Considering the great economic importance of oak for forest management, the objectives of this study were to determine the proportion of trees with frost ribs in the stand (I), to characterize frost ribs (frost cracks) (II), to compare selected morphological characteristics of trees with and without frost ribs (III), and to compare the basic density of wood and moisture content (in winter) of trees with and without frost ribs (IV). Based on objectives I and II, the forest management significance of frost ribs had been assessed. Meanwhile, based on objectives III and IV, the distinguishing characteristics of the population of trees with frost ribs (frost cracks) had been determined.

Materials and methods

Study area and study design. The study area was located in western Poland. The region is located in a temperate climate zone, in an area of intermingling oceanic and continental influences. The average annual temperature is about 8.5°C, with about 24 days of frost during the year and low precipitation, especially in the southern and eastern parts.

Oak is the second dominant species in the region's forests, after the Scots pine *Pinus sylvestris* L. Of particular importance for the breeding of this species is the area called the 'Krotoszyn plate' or 'Krotoszyn oaks'. This is one of the largest oak forest complexes in Poland, with specific growth conditions, where the oak develops a flat root system. Because of this, it is susceptible to droughts. A characteristic feature is the very good quality of the wood. Trees grow in thickness slowly, the annual rings are narrow, and the wood has a uniform color. For this reason, it is used mainly for veneer.

The research was carried out in the winter of 2020/2021 and 2021/2022, at three locations, in 18 sessile oak *Q. petraea* stands. Of these plots, 8 were established in the area of the Forest Experimental Station in Murowana Goślina (MU), 5 in the area of the Grodzisk Forest District (GR), and 5 in the area of the Krotoszyn Forest District (KR) (Fig. 1).

The age of the trees was between 63 and 147 years. The proportion of oak in the species composition ranged from 50% to 100%, breast height diameter from 20 to 50 cm, and average height from 17 to 32 m. The areas of the stands ranged from 1.8 to 19.6 hectares, and gave a total of 98.9 hectares. All trees with frost ribs were marked in the entire area. A total of 187 damaged trees were marked. However, sample plots were designated to assess the proportion of trees

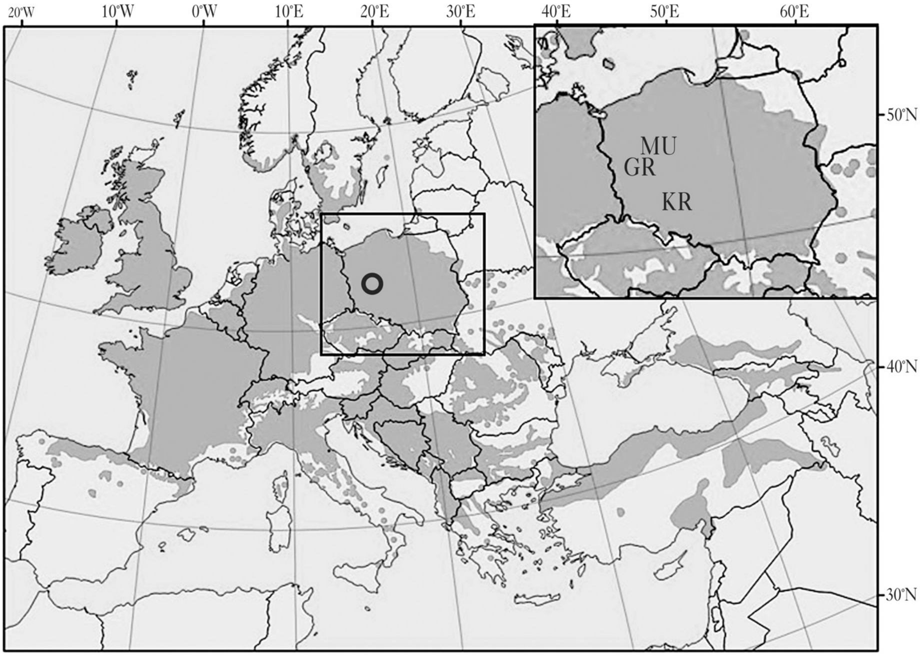

Fig. 1.
The natural range of sessile oak and the location of the research area (source: www.euforgen.org)
Note: Forest Experimental Station in Murowana Goślina (MU), Grodzisk Forest District (GR), Krotoszyn Forest District (KR)

with frost ribs. Their size and number depended on the age and area of the stand. The research method assumed that the total sample area would be from about 5% to about 10% of the stand area. Assessment of the proportion of trees with frost ribs in the stand was carried out on an area of 7.91 hectares (Table 1). In the sample plots, all trees were counted, including trees with frost ribs.

All sampled trees in the sample plots, including trees with frost ribs, were numbered. Next, the characteristics of all trees with frost ribs were measured: breast height diameter [cm], height [m], and crown length [m]. To compare height and crown length, the nearest sampled tree without frost ribs and with a similar breast height diameter (±2 cm) to that of the tree with frost ribs was selected. Tree height and crown length were measured using a Suunto altimeter (Suunto, Vantaa, Finland), with an accuracy of 0.5 m. The breast height diameter was measured using a forest calliper, with an accuracy of 1 cm. A total of 374 trees were measured: 187 damaged (with frost ribs) and 187 undamaged (without frost ribs) trees.

Measurement of frost ribs. The length of frost ribs was measured with an accuracy of 1 cm, or in the case of very long ribs, with a Nikon Forestry Pro laser altimeter (Nikon, Tokyo, Japan) with an accuracy of 10 cm. If there was more than one frost rib on a trunk, all frost ribs were measured. In turn, the position of the frost rib relative to north was determined using a compass. When there were more frost ribs on the trunk, the compass directions were determined for each frost rib separately. A total of 284 frost ribs were measured.

Sampling procedure. For the analysis of selected physical properties of wood, 60 trees with frost ribs and 60 trees without frost ribs were randomly selected. Thirty-four were located in stands

Table 1.
Characteristics of stands with sample area (source: www.bdl.lasy.gov.pl)

Code	No.	Stand area [ha]	Age	Share of oak in the species composition [%]	Breast height diameter (dbh) [cm]	Height [m]	Sample area [ha]
MU	1	8.21	74	70	25	27	0.42
	2	2.18	78	50	22	20	0.21
	3	4.72	82	70	24	26	0.48
	4	2.91	102	100	28	26	0.30
	5	8.76	111	100	30	26	0.70
	6	7.99	121	100	36	27	0.75
	7	1.80	124	80	39	29	0.15
	8	2.10	146	100	44	27	0.20
GR	9	4.23	63	100	20	18	0.20
	10	4.07	68	90	20	17	0.22
	11	3.67	68	90	20	19	0.36
	12	3.48	114	80	39	28	0.40
	13	1.75	114	100	39	29	0.20
KR	14	19.60	85	60	33	26	1.14
	15	2.51	87	80	32	27	0.28
	16	6.93	90	100	45	29	0.60
	17	3.18	127	100	44	30	0.30
	18	10.81	147	80	56	32	1.00

of the Forest Experimental Station in Murowana Goślina (MU), and twenty-six in stands of the Grodzisk Forest District (GR).

In the trunk of each mean sample tree, an increment core was collected at breast height (130 cm above ground, north side of the trunk) using an increment borer. From this, 2 cm-long samples were cut, each representing a different part of the stem cross-section. The first sample (H1) was located 0.5 cm from the pith. The second sample (H2) was collected 0.5 cm from the boundary between heartwood and sapwood. The third sample (S) was located in the sapwood, a minimum of 0.5 cm from the heartwood (Tomczak *et al.*, 2018).

Measurement of wood properties. Properties in green wood were measured *in situ* immediately after obtaining the increment cores. After labeling, samples were weighed using an electronic balance with an accuracy of 0.01 g. Next, the volume of the sample was determined. We measured the length (L) of each sample using a caliper with an accuracy of 0.01 cm. The diameter (D) of samples was 5.15 mm. Based on the measured length and the diameter, the volume of each sample was calculated using equation (1):

$$Vw = \pi \cdot (0.5D) \cdot (0.5D) \cdot L \text{ [cm}^3\text{]} \quad (1)$$

where:

Vw – the volume above the fiber saturation point,
D – the sample diameter (=5.15 mm),
L – the length.

After taking measurements on fresh wood in the field, all sample pieces were transported to a laboratory. In the laboratory, the samples were dried at 105°C. Drying continued until the water content reached 0% and the weight of the sample was constant. The samples were then weighed and measured in dry state, by the same method as for the green wood measurements. The absolute moisture content (MC) was then calculated from equation (2), and the basic density (q) from equation (3):

$$MC = ((m_w - m_d) / m_d) \cdot 100 \ [\%] \tag{2}$$

$$q = m_d / V_w \ [g \cdot cm^{-3}] \tag{3}$$

where:

m_w – the green mass,

m_d – the oven-dry mass,

V_w – the volume above the fiber saturation point.

Statistical analyses. The Lilliefors test was used to evaluate the normality of the data distribution. A statistically significant result allows the rejection of the null hypothesis of normality of the distribution. The non-parametric Kolmogorov-Smirnov test was used to verify differences between two independent groups, while post hoc multiple comparisons of mean ranks were used for three or more independent groups. Moreover, the correlation matrix was determined for the studied characteristics. In this case, Spearman's rho was used. Statistical inference was performed at a significance level of $\alpha \leq 0.05$. Calculations were performed using the Statistica 13.1PL software package (TIBCO Software Inc., 2017).

Results

Damaged trees frequency in stands. There were 1904 trees in the sample plots designated in the stands, including 124 trees with frost ribs. The proportion of trees with frost ribs was thus calculated as 6.5%. At the MU location there were 632 trees in total, 55 of which had damage; at the GR location there were 406 trees, 12 of which had damage; and at the KR location there were 866 trees, 57 of which had damage. Respectively 8.7%, 3.0% and 5.2% trees.

Characteristics of frost ribs. There were 124 trees with one frost rib, 40 trees with two ribs, 12 trees with three ribs, and 11 trees with four ribs. Relative to the total number of trees (187), these sets represent 66.3%, 21.4%, 6.4%, and 5.9% respectively. A total of 284 frost ribs were measured; their average length was 149 cm.

The highest number of frost ribs was found on the south side of tree trunks, accounting for about 36% of the measured frost ribs. The smallest number was on the northeast side (2.8%) (Fig. 2a). The longest rib were found on the west side (249 cm), and the shortest on the northwest side (97 cm) (Fig. 2b).

There were 124 frost ribs measured at the MU location, 19 at the GR location, and 141 at the KR location. In terms of compass directions, the highest numbers of ribs in particular locations were found on the northwest (MU), west (GR), and south (KR) sides. The longest rib (249 cm) were found at the KR location, and the shortest (97 cm) at the GR location. The average length of ribs at the MU location was 140 cm.

Breast height diameter, tree height, crown length. There were 187 trees with frost ribs in a total area of 98.9 hectares. The height, breast height diameter, and crown length of 187 comparison sound trees, without frost ribs, were also measured. There were no statistically significant differences between height, breast height diameter ad crown length of trees with and without frost ribs (Table 2).

Frost rib length correlated significantly with tree height ($p<0.05$; 0.14). The analysis showed that the taller tree were characterized by shorter frost ribs. In the case of breast height diameter and crown length, the correlation was not statistically significant.

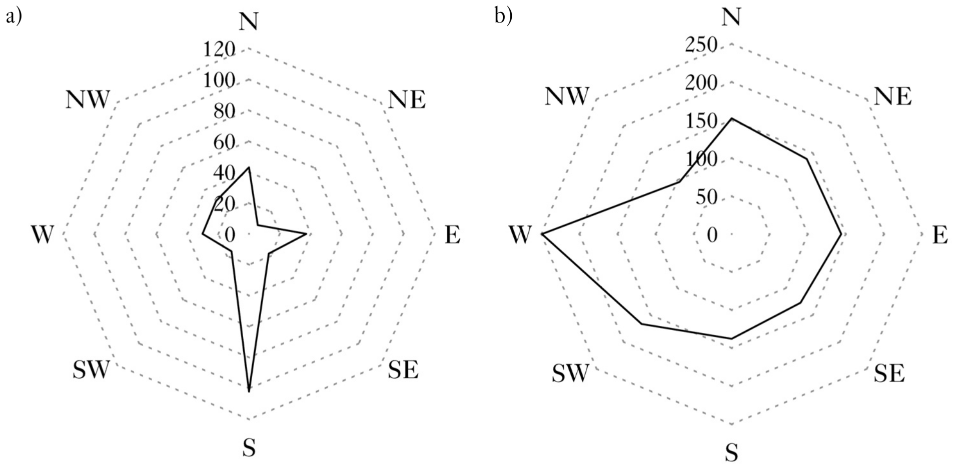

Fig. 2.
Number (a) and length (b) of frost ribs depending on geographic direction
N – north, S – south, W – west, E – east, NW – north-west, NE – north-east, SW – south-west, SE – south-east

Table 2.
Height, breast height diameter (dbh) and crown length of sampled trees with and without frost ribs

		Trees with frost ribs			Trees without frost ribs			*p*-value
		mean	SD	VC [%]	mean	SD	VC [%]	
Height [m]	MU (n=87)	23.9	3.5	14.7	24.5	3.6	14.8	Ns*
	GR (n=21)	18.5	4.2	22.9	18.1	4.0	22.2	Ns*
	KR (n=79)	27.6	2.5	9.2	26.7	3.2	11.9	Ns*
	All	24.9	4.3	17.3	24.7	4.3	17.5	Ns*
Breast height diameter (dbh) [cm]	MU	36.0	8.5	23.6	36.1	8.0	22.2	Ns*
	GR	26.0	10.8	41.3	25.7	11.0	42.8	Ns*
	KR	38.6	7.7	19.9	38.7	7.6	19.7	Ns*
	All	36.0	9.2	25.6	36.0	9.1	25.1	Ns*
Crown length [m]	MU	8.3	2.2	26.4	8.9	2.8	31.0	Ns*
	GR	9.9	4.4	44.5	9.0	3.8	42.3	Ns*
	KR	7.7	2.7	35.1	7.8	2.6	32.9	Ns*
	All	8.2	2.8	34.0	8.4	2.8	33.8	Ns*

Ns* – not statistically significant
Note: MU – Murowana Goślina, GR – Grodzisk, KR – Krotoszyn, SD – standard deviation, VC – coefficient of variations

Basic density and moisture content. The basic density of trees with frost ribs was 0.592 g/cm^3, while that of trees without frost ribs was 0.596 g/cm^3. The differences were not statistically significant ($p<0.05$). The wood moisture content of trees with frost ribs was about 3% higher than that of trees without frost ribs. The differences for moisture content was statistically significant (Table 3).

Basic density decreases and moisture content increases in the direction from pith to bark, in both trees with and without frost ribs. The basic density of H1 and H2 samples was very similar for the compared groups of trees (with and without frost ribs). A slight difference for basic density was observed for S samples (Fig. 3a). For MC, lower values were obtained for trees without frost ribs, on the entire cross-section of the trunk (Fig. 3b). There were no statistically significant differences between trees with and without frost ribs for all samples on the cross-section of the trunk.

Table 3.
Basic density and moisture content (MC) of wood of sampled trees with and without frost ribs

	n	Trees with frost ribs			Trees without frost ribs			*p*-value
		mean	SD	VC [%]	mean	SD	VC [%]	
Basic density [g/cm^3]	174	0.592	0.054	9.2	0.596	0.049	8.3	Ns*
MC [%]	174	75.1	14.0	18.7	72.1	10.9	15.1	0.02

Ns* – not statistically significant
MC – moisture content, SD – standard deviation, VC – coefficient of variability, n – number of samples

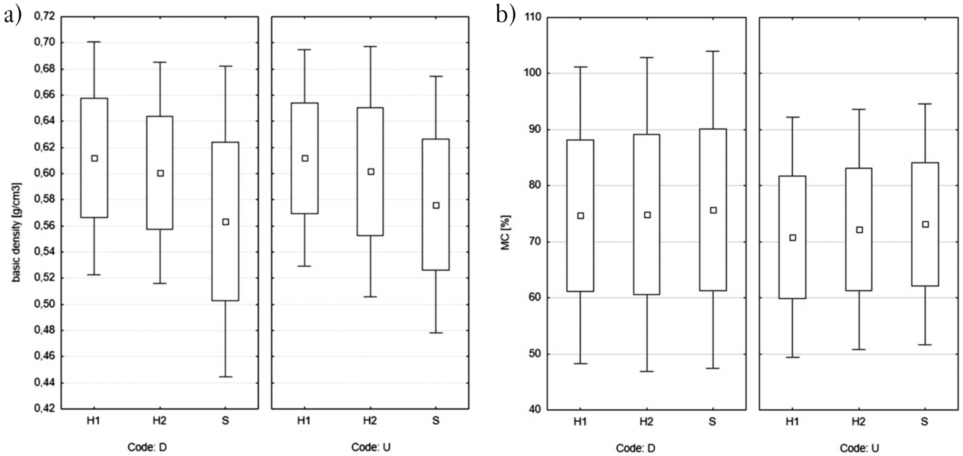

Fig. 3.
Radial differences of basic density (a) and moisture content of wood (b) trees with (Code: D) and without (Code: U) frost ribs
H1 – samples were located 0.5 cm from the pith, H2 – samples were located in heartwood, 0.5 cm from the boundary between heartwood and sapwood, S – samples were located in the sapwood, 0.5 cm from the heartwood; whiskers correspond to mean ±1.96·SD, boxes represent mean ±SD, dot represent mean value

Discussion

Frost cracks are natural wood defects that decrease the wood quality. Through the crack, the tree can be infected by wood-degrading fungi. As a result, the strength of the wood decreases (Mania and Tomczak, 2020). We estimated that in oak stands, the proportion of trees with frost cracks was about 6.5%.

Breast height diameter, tree height and crown length of trees with and without frost ribs were similar. For this reason, it is not possible to formulate guidelines for silviculture based on morphological characteristics that might be used to identify trees particularly susceptible to crack formation. Trees with and without frost ribs also do not differ in basic density. The opposite results presented Mania and Tomczak (2020), who obtained statistically significant differences when comparing the wood density of trees with and without frost ribs. However, we showed a statistically significant difference for moisture content. A similar result was obtained by Cinotti (1989). The samples were taken during the winter season, in February and March. In winter, the moisture content of the wood of living trees tends to be higher than at other seasons of the year (Tomczak *et al.*, 2021). The moisture content trees with frost ribs (75.1%) was 3 percentage points higher than that sampled trees without frost ribs (72.1%). A very similar value (74%) for samples harvested in February was reported by Longuetaud *et al.* (2016). Cinotti (1989) obtained values about 10 percentage points higher.

We also analyzed basic density and moisture content on the cross-section of the trunk. Samples were obtained from heartwood and sapwood. In heartwood, the first sample was obtained near the pith and the second sample near the boundary of heartwood and sapwood. In this case, we do not found differences between samples obtained from trees with and without frost ribs. Generally on the cross-section of the trunk, both basic density and moisture content changed characteristically for ring-porous species (Longuetaud *et al.*, 2017; Jakubowski and Dobroczyński, 2021; Tomczak *et al.*, 2022b). The basic density decreased, and moisture content increased along the radius.

The highest number of frost ribs occurred on the southern side of the trunk. A similar relationship was observed in birch stands (Kula *et al.*, 2006). The parts of trees growing in the sun have the most extreme temperature minima and maxima, the highest rate of temperature change, and the highest number of freeze-thaw events. The number of freeze-thaw events is greatest in the sunny parts of the tree top, and decreases toward the base of the trunk and from the trunk surface to the center of the trunk (Mayr *et al.*, 2006). We do not know the temperature gradient on the cross-section of the trunk. Perhaps cracks are more likely to form on the south side, when due to the temperature difference, the wood of the outer layers of the tree trunk freezes and the inner layers do not. Shrinkage of the wood of the outer layers combined with non-shrinkage of the wet wood inside the trunk increases the risk of cracking (Ishida, 1963).

We also do not know what weather conditions prevailed in the days preceding the formation of the cracks. Mayer-Wegelin *et al.* (1962) claim that frost cracks form only during prolonged frosts, that is, they are not the result of a sudden drop in temperature. Dziurzyński (2005) analyzed the mechanism of crack formation in *Platanus* × *acerifolia* (Aiton) Willd. and *Quercus* growing in urban conditions, and found that cracks appear at temperatures around –12°C.

Frost cracks usually form in the lower part of the trunk. Kula *et al.* (2006) believe that the concentration of cracks in the lower part of the trunk corresponds to the places most exposed to bending stresses and having the least ability to withstand bending load. We assume, that the occurrence of cracks in the lower part of the trunk correlates rather with the size and number of medullary rays, moisture content of wood and low temperatures at ground level. Mania and Tomczak (2020) noted that frost cracks and rot develops mainly along the medullary rays. The medullary rays are cellular structures with very low tensile strength. Additionally, in oak, the moisture content in the base of the tree is higher than in the top (Tomczak *et al.*, 2018).

Frost ribs are wood defects that significantly reduce the quality and value of timber. For this reason, it is important to understand the various factors that may be involved in the occurrence of frost cracking, to mitigate the negative effects through tree breeding. Several suggestions have been given as to the causes of frost cracks. These suggestions are sometimes difficult to verify unequivocally, as the accompanying experiments are often qualitative in nature. More accurate quantitative studies, however, require an individual approach to each frost-cracked tree.

Conclusions

We estimated that in sessile oak stands, the proportion of trees with frost rib (crack) was about 6.5%. Even a few of defective trees reduces the proportion of valuable wood. We found that trees with frost ribs have a statistically significantly higher moisture content in winter than sound trees (without frost ribs). Moisture content is specific tree characteristics, which is not used through breeding. To mitigate the negative effects through breeding, it is necessary to rely on specific tree characteristics. The analysis indicated that the taller trees were characterized by shorter the frost ribs. We found no differences in breast height diameter, height or crown length between trees with and without frost ribs. For this reason, it is not possible to formulate guidelines for silviculture based on morphological characteristics that might be used to identify trees with higher sensitivity to low temperatures.

Authors' contributions

Conceptualization, methodology – A.T.; validation – A.T., K.T., W.G., M.D., I.P., J.T. and T.J.; writing of first manuscript draft – A.T. and K.T.; review and editing of manuscript versions – A.T., K.T. G.W. and T.J.; visualization – A.T. and K.T.

Conflicts of interest

The authors declare no conflict of interest.

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STRESZCZENIE

Występowanie i charakterystyka listew mrozowych w drzewostanach dębu szypułkowego

Pęknięcie mrozowe jest wadą drewna, która istotnie obniża jakość dębowego surowca drzewnego. Ze względu na wysoki udział dębu w lasach i jego znaczenie gospodarcze celami pracy były: określenie udziału w drzewostanie drzew z listwami mrozowymi (I), charakterystyka listew mrozowych (II), porównanie wybranych cech morfologicznych drzew z listwami mrozowymi i bez listew mrozowych (III) oraz porównanie gęstości i wilgotności drewna drzew (w okresie zimowym) z listwami mrozowymi i bez nich (IV). Na podstawie celów I i II ocenione zostało znaczenie gospodarcze pęknięć mrozowych. Natomiast na podstawie celów III i IV określone zostały cechy wyróżniające populację drzew z pęknięciami mrozowymi (listwami mrozowymi). Badania wykonano w 3 lokalizacjach, w 18 drzewostanach dębowych ze znacznym udziałem dębu szypułkowego. Na terenie Leśnego Zakładu Doświadczalnego w Murowanej Goślinie wybrano 8 drzewostanów, na terenie Nadleśnictwa Grodzisk 5, na terenie Nadleśnictwa Krotoszyn również 5 (ryc. 1, tab. 1). Na kołowych powierzchniach próbnych rosły 1904 drzewa, z czego 124 drzewa z listwami mrozowymi, co stanowiło 6,5% ogółu drzew. Na 124 drzewach występowało 1 pęknięcie mrozowe, na 40 drzewach 2 pęknięcia, na 12 drzewach 3, a na 11 drzewach 4 pęknięcia. Łącznie pomierzono 284 listwy mrozowe. Ich przeciętna długość wynosiła 149 cm. Pomierzono również wysokość, pierśnicę i długość korony 187 drzew porównawczych (tab. 2). Nie stwierdzono statystycznie istotnych różnic pomiędzy cechami morfologicznymi drzew z listwami mrozowymi i bez nich. Gęstość drewna drzew z listwami mrozowymi wynosiła 0,592 g/cm^3, natomiast drzew bez listew mrozowych 0,596 g/cm^3, przy czym różnica nie była statystycznie istotna ($p \leq 0,05$). Na przekroju poprzecznym pnia gęstość drewna wykazywała zmienność charakterystyczną dla gatunków pierścieniowo-naczyniowych (ryc. 3a). Wilgotność drewna drzew z listwami mrozowymi była o około 3% wyższa niż drzew bez listew mrozowych. W tym przypadku różnica była statystycznie istotna (tab. 3). Udział drzew wadliwych w drzewostanach został oszacowany na kilka procent. Tak pozornie niewielki udział drzew uszkodzonych zmniejsza udział cennego drewna, ponieważ wzdłuż pęknięcia występuje zazwyczaj rozkład drewna, który nawet w początkowej fazie rozwoju może istotnie zmniejszyć wytrzymałość mechaniczną drewna. Nie stwierdzono różnic w pierśnicy, wysokości i długości korony pomiędzy drzewami z listwami mrozowymi i bez nich. Być może istnieją inne cechy niezidentyfikowane i nieuwzględnione w przeprowadzonym doświadczeniu. Stwierdzono jednak, że drzewa z listwami mrozowymi charakteryzują się w okresie zimowym wyższą wilgotnością drewna niż drzewa bez uszkodzeń, niezależnie od położenia próbki na przekroju poprzecznym pnia (ryc. 3b). Biorąc pod uwagę teoretyczne podstawy powstawania pęknięć mrozowych, można założyć, że dużą wrażliwością na niskie temperatury charakteryzują się drzewa o wyższej wilgotności. Z kolei lokalizacja listew (kierunek geograficzny) (ryc. 2) sugeruje, że powstają one po stronie pnia, gdzie występują najbardziej ekstremalne minima i maksima temperatury, największe tempo zmian temperatury oraz największa liczba zdarzeń typu zamrażanie-odmrażanie.