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Distribution of Frost Injuries in the Wood of Conifers

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Abstract—The distribution of frost injuries in earlywood and latewood, in different zones of stem (with respect to height, diameter, and circumference), and at the bases of large roots has been studied in Siberian spruce (*Picea obovata* Ledeb.) and Siberian larch (*Larix sibirica* Ledeb.) at the northern limit of their ranges (the Obsko-Tazovskaya forest–tundra). It has been shown that a high frequency of frost injuries, especially in spruce, is characteristic of the study region. Mass frost injuries occur only in thin trees, mainly in the lower part of stems. Guidelines for collecting and preparing wood samples for the study of frost injuries are proposed.

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Recently, increasing attention has been devoted to studies on the impact of extreme environmental factors on the composition and structure of plant and animal populations and their role in the transformation and degradation of natural and artificial ecosystems. In particular, this concerns extreme climatic events, which are often disastrous and have serious consequences. Many publications have addressed this problem (Budyko, 1974; Borisenkov and Pasetskii, 1988; Krenke and Chernavskaya, 1998; *Izmenenie klimata…*, 2003). In this context, it is important to analyze the intensity and frequency of these events over long periods of time using both empirical data and information derived from the literature and other relevant sources.

Tree rings are a reliable source of information on climates of the distant past. Studies of variation in the annual increment, density, and chemical composition of wood have provided a basis for many reconstructions of the dynamics of important climatic parameters over hundreds or thousands of years (Vaganov *et al.*, 1996; Briffa *et al.*, 2002). In recent years, extreme climatic events have been reconstructed by analyzing pathological structures in wood, such as the annual rings with a layer of compressed, deformed cells destroyed by frosts, which are referred to as frost rings (Glerum and Farrar, 1966); rings with weakly lignified latewood cells (light rings); layers of latewood cells located within earlywood (false rings); or the absence of radial increment (missing rings). However, most authors merely note the presence of a certain pathological structure (Delwaide *et al.*, 1991; Stöckli and Schweingruber, 1996; Hantemirov *et al.*, 2000, 2004), whereas data on the distribution of such structures (in particular, frost injuries) in tree stems are usually fragmentary. It is known, for example, that frost rings in trees and shrubs occur mainly in young plants (Glerum, 1975; Nilov, 1979), and some data on the distribution of pathological structures, including frost rings, in the stem wood of Siberian larch and Siberian spruce in the Polar Urals and northern Ob region are available (Gurskaya, 2000, 2002). Poor knowledge of trends in the distribution of such structures is responsible for difficulties in collecting representative wood samples for dating and the chronological reconstruction of harmful climatic events such as frosts.

In this paper, we present data on the distribution of frost injuries in earlywood and latewood, in different zones of tree stem (with respect to height, diameter, and circumference), and at the bases of large roots in Siberian spruce (*Picea obovata* Ledeb.) and Siberian larch (*Larix sibirica*) at the northern limit of their ranges.

STUDY REGION, OBJECTS, AND METHODS

Studies were performed in the Obsko-Tazovskaya forest–tundra province on the left bank of the Ob river (Govorukhin, 1963). The study area is a plain with hills and ridges that rise to 60–125 m a.s.l. and are composed of sand–loam deposits. Larch, spruce–larch, and birch–spruce–larch forests of the shrub–moss–lichen type markedly vary in density and alternate with shrub tundras and bogs. This is a region of long, cold winters with strong winds and short, cool summers with frequent frosts (Orlova, 1962). According to data from the Salekhard weather station, the highest and lowest monthly average temperatures are 13.3°C in July and –24.5°C in January. The periods with daily average temperatures above 0 and 5°C are 132 and 99 days,

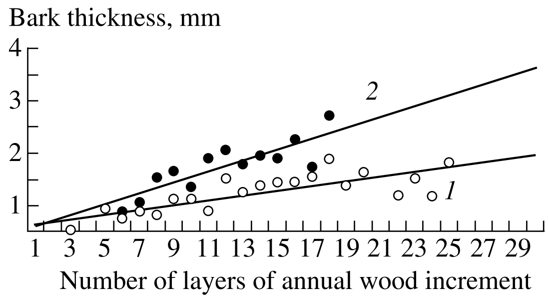

Fig. 1. Changes in the thickness of stem bark in (*1*) Siberian spruce and (*2*) Siberian larch in the first 30 years at a height of 0.2 m.

respectively. The frost-free period varies from 30 to 130 days. On average, spring frosts occur until June 10, but the latest frost was recorded on June 28; autumn frosts begin on September 7, but the earliest frost was recorded on August 15. Annual precipitation averages 400 mm, but potential evaporation is only 250 mm, which is evidence that the climate is excessively humid.

Frost injuries in Siberian spruce and Siberian larch were studied in three plots located 3–12 km away from the city of Labytnangi (66°40′–66°44′ N, 66°20′–66°22′ E). Two plots were in open spruce–larch forests of different densities, and the third plot was in an open larch forest. Ten model trees of each species (6–12 m high and 10–20 cm in diameter) were selected in each plot and cut to take wood samples (crosscuts) at a height of 0.2 m and along the entire stem, at 1-m intervals. Crosscuts were also made at the base of the largest root, at a distance of 15–20 cm from the root collar. Bark thickness in the lower part of the stem reached 1–1.5 cm in spruce and 3 cm in larch, and the number of tree rings on stumps (0.2 m above the ground surface) varied from 100 to 130. In addition, four radial core samples (along two perpendicular axes) were taken from 108 spruce and 190 larch trees at heights of 0.2 and 1 m. These trees differed in age (according to the number of rings on the stump, 10–160 years) and, hence, in height (0.5–12 m) and diameter (0.5–20 cm).

The surface of all crosscuts and cores was thoroughly trimmed with a sharp cutting tool to make their cellular structures more prominent. The width of tree rings was measured with an accuracy of 0.01 mm, and individual tree-ring chronologies were absolutely dated using the TSAP and COFECHA programs. We also determined the biological (cambial) age of tree rings at a certain height (without taking into account the pith ring). Each ring was carefully examined under an MBS-10 binocular microscope at 40× magnification. The location of injury within a frost ring (in earlywood or latewood) was recorded. On the whole, 11 500 rings in spruce and 24 700 rings in larch were studied.

In spruce, tree-ring width at heights of 0.2 and 1 m averaged 0.53 ± 0.02 and 0.58 ± 0.03 mm, respectively, and the rings were wider in the center of the stem than at its periphery. In larch, the respective values were 0.68 ± 0.04 and 0.65 ± 0.04, and central rings were narrower than peripheral.

RESULTS AND DISCUSSION

Chronology of frost injuries and their distribution in earlywood and latewood. Between 1843 and 1999, frosts resulting in damage to cells and tissues in spruce and larch wood occurred with a high frequency: on average, every one or two years (table). In some periods (1880–1886, 1895–1899, 1904–1911, 1923–1933, 1944–1951, 1953–1972, 1976–1983, and 1990–1995), they repeated every year. Data on frost injuries in spruce between 1843 and 1871 are absent from the table, because model trees of this species were 29 years younger than larch trees. During the past 158 years, there were 109 years in which trees were injured by frosts. Such injuries more often occurred in spruce (in 85 out of 129 years) than in larch (66 out of 158 years), because spruce is less frost-hardy and has a much thinner bark (Fig. 1). In most cases, both species were damaged in the same year, but in some instances (in 1923, 1924, 1946, 1955, 1967, 1990, and 1991) frost rings were formed only in larch. This may be explained by nonuniformity in the spatial distribution of frosts and, possibly, differences in the period of cambial activity, which begins earlier and ceases later in larch than in spruce. Due to these and several other factors, the same frost never damages all trees growing in a given area. The proportion of damaged trees after a severe frost may reach 80%, but, in our opinion, the cases when it exceeds 20% may already be regarded as mass damage.

Frost injuries in both species occurred more often in earlywood than in latewood: in 63 vs. 55 years in spruce and in 54 vs. 35 years in larch (table). This is evidence that late spring and early summer frosts are more frequent in the study region than late summer and early autumn frosts. Tree rings with frost injuries in both layers appeared in some years only in spruce (31 years), only in larch (13 years), or in both species (in 1941, 1945, 1963, and 1988). The same frost sometimes damaged earlywood in one tree and latewood in another tree, depending on the degree of tree ring development and individual cold hardiness. In spruce, two frost injuries in the same ring appeared in some years (1881, 1882, 1884, 1891, 1893, 1895, 1896, 1913, 1917, 1918, and 1945). This is evidence for two frosts within the same growing season (Gurskaya and Shiyatov, 2002). The frost-free period in such years decreases to two or three weeks.

Radial distribution of frost injuries. Figure 2 shows the distribution of frost injuries in 118 spruce and 200 larch trees at a height of 0.2 m depending on stem diameter (without bark). These injuries concentrate in the central part of the stem (2.0–2.5 cm in diameter), sharply decrease in number as its diameter increases, and disappear when it exceeds 5–6 cm. This observation agrees with published data. In red pine

Years of frost ring formation (+) in earlywood (EW) and latewood (LW) in Siberian spruce and Siberian larch between 1843 and 1999

Year	Spruce		Larch		Year	Spruce		Larch	
	EW	LW	EW	LW		EW	LW	EW	LW
1843			+	+	1932	+	+		+
1844			+	+	1933		+		
1845			+	+	1937		+	+	
1847			+		1938	+		+	
1849				+	1940			+	
1852				+	1941	+	+	+	+
1854			+		1944	+			+
1856				+	1945	+	+	+	+
1857				+	1946			+	+
1858				+	1947	+	+	+	
1862			+	+	1948	+			+
1866				+	1949	+		+	
1867				+	1950	+		+	
1868			+		1951	+	+	+	
1870				+	1953	+		+	
1872		+		+	1954	+		+	
1880	+	+			1955			+	
1881	+	+			1956	+		+	
1882	+	+		+	1957	+	+	+	
1883	+				1958	+	+	+	
1884	+	+			1959	+			
1885		+			1960	+		+	
1886		+		+	1961	+			+
1890	+				1962	+	+		
1891	+	+			1963	+	+	+	+
1993	+	+			1964	+		+	
1895	+	+			1965	+			
1896	+				1966	+		+	
1897	+				1967			+	
1898	+				1968	+			
1899	+				1969		+	+	
1901		+			1970	+	+		
1902		+			1971		+		+
1904	+				1972		+		
1905	+				1974		+		
1906		+			1976		+	+	
1908	+	+			1977	+		+	
1909	+	+			1978	+	+		+
1910	+				1980		+		+
1911	+	+			1981	+	+	+	
1913	+	+	+		1982		+	+	
1916		+			1983	+		+	
1917		+			1985	+		+	
1918	+	+	+		1986	+	+	+	
1919		+			1987		+	+	+
1920	+	+			1988	+	+	+	+
1923			+	+	1990			+	
1924				+	1991			+	+
1925		+		+	1992	+	+	+	+
1926	+	+		+	1993	+			
1927		+			1994	+			
1928	+				1995	+	+		
1929	+	+			1997	+	+		
1930	+		+	+	1999		+		
1931		+							

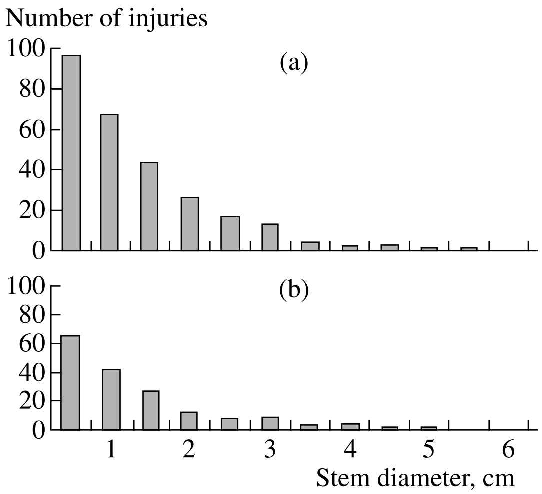

Fig. 2. Distribution of frost injuries in (a) Siberian spruce and (b) Siberian larch depending on stem diameter without bark at a height of 0.2 m.

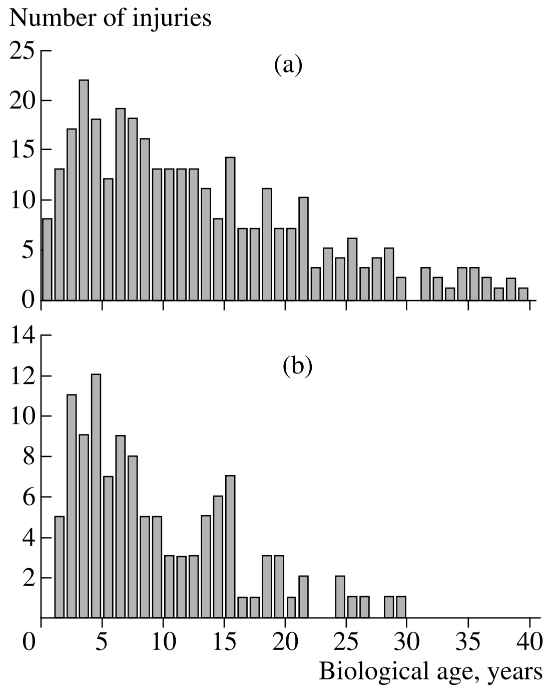

Fig. 3. Distribution of frost injuries depending on the biological age of tree rings in (a) Siberian spruce and (b) Siberian larch at a height of 0.2 m.

(*Pinus resinosa* Ait.) growing in Canada, frost damage to trees was rarely observed when their diameter was greater than 8 cm (Fayle, 1981). In frutescent *Pinus mugo* Tutta, the maximum diameter of plants at the time of frost ring formation proved to be approximately 2.5 cm, with the total number of rings being about 20 (Stöckli and Schweingruber, 1996).

The distribution of frost injuries has a similar pattern in the plot where the abscissa shows the biological age of tree rings (without the pith ring) at a height of 0.2 m (Fig. 3). The latest frost injuries were detected in the 40th ring in spruce and the 29th ring in larch; 80% of injuries were confined to the first 30 rings in spruce and to the first 20 rings in larch. In addition, we have data on the radial distribution of frost injuries in ten spruce and ten larch trees at different heights. In spruce, the latest injury at a height of 1 m was detected in the 47th ring; at heights of 2–7 m, the latest injuries were detected in rings whose biological age was 17, 7, 10, 5, 11, and 6 years, respectively. In larch, the latest injury at 1 m was detected in the 28th ring; the latest injuries at heights of 2–5 m were in rings that were 16, 26, 4, and 17 years old. Therefore, frost rings at heights of 0.2 and 1 m cease to appear at approximately the same age: 40–47 years in spruce and 28–29 years in larch. In stem segments that are located higher, the biological age of tree rings with the latest frost injuries is younger (4–26 years).

Thus, frost injuries in spruce and larch were revealed only in those segments in which stem diameter (without bark) during frosts was no more than 5–6 cm and bark thickness did not exceed 2.0–2.5 mm. Thicker stems accumulate more heat during the daytime, and temperature in the cambial zone remains above zero during night frosts; hence, frost injuries are rare or absent. The fact that the incidence of frost injuries strongly depends on stem diameter and bark thickness is confirmed by the results of studies on such injuries in Siberian juniper (*Juniperus sibirica* Burgsd.) growing in the Polar Urals. In this shrub, which reaches 1.5 m in height, the base diameter of branches is up to 10–15 cm, but bark is very thin, 1.0–1.5 mm; hence, frost injuries occur at any age (the life span of this species is about 850 years) (Hantemirov *et al.*, 2000).

Length of frost injuries relative the circumference of a tree ring. Figure 4 shows the distribution of frost injuries extending over different proportions of tree ring circumference in 35 spruce and 32 larch trees at a height of 0.2 m. Damage to xylem all over a ring was most widespread in both species. Frost injuries extending over 40–80% of the circumference were also frequent. They were confined to the widest parts of eccentric rings that usually contained abnormal (compressed) wood. Injuries of such a length appear because the activity of cambium in these parts is markedly higher. Tree rings with injuries extending for 10–30% of their circumference occurred rarely, mainly near knots and places of wound wood development.

Distribution of frost injuries along tree stem and at the bases of large roots. Figure 5 shows the distribution of frost injuries found at different heights in the first 30 rings in spruce and 20 rings in larch. Tree height averaged 6.5 m (ranging from 3 to 11 m) in spruce and 7.5 m (ranging from 6 to 10 m) in larch. Six spruce and seven larch trees were higher than 7 m. The greatest proportion of injuries in both species was found at a height of 0.2 m. Published data confirm that trees contain frost damage mainly in the lower part of the stem,

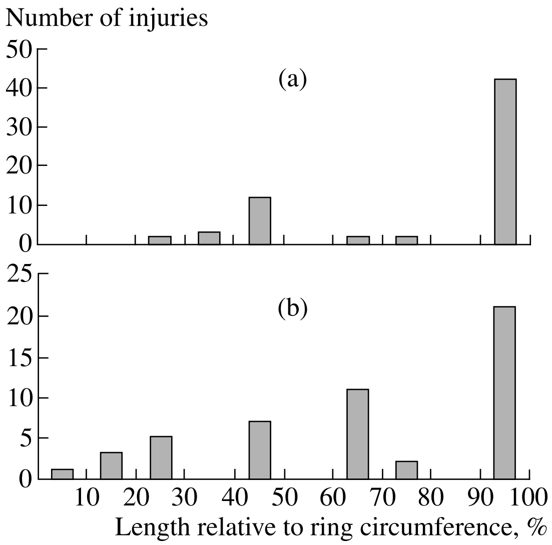

Fig. 4. Distribution of frost injuries along the circumference of tree rings in (a) Siberian spruce and (b) Siberian larch at a height of 0.2 m.

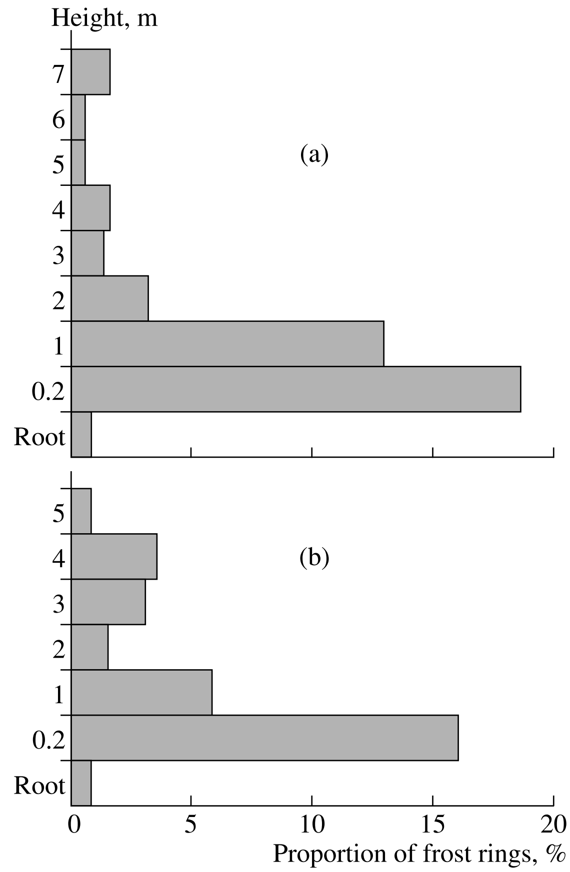

Fig. 5. Distribution of frost injuries along tree stem in (a) Siberian spruce and (b) Siberian larch.

0.3–0.5 m above the ground (Glerum, 1975; Nilov and Chertovskoi, 1975; Nilov, 1979; Fayle, 1981).

The proportion of frost rings was also relatively large at a height of 1 m, especially in spruce, but it sharply decreased in the upper segments of the stem. The uppermost frost injuries in spruce and larch were located at heights of 7 and 5 m, respectively. It is noteworthy that in red pine from Ontario (Canada) a frost ring was found at a height of 14 m (Fayle, 1981). Frost rings at the bases of large roots in spruce and larch occur rarely, and their proportion among the first 30–50 rings is only 1–2%.

The distribution of frost injuries along tree stems agrees well with the distribution of subzero temperatures during frosts. Because of radiational cooling at night, the surface temperatures of the soil and plant cover, including tree stems, decrease to the lowest values. The ground air layer also cools to below zero, and a temperature inversion is observed: air temperature increases with height and often rises above zero at a height of 2 m if a frost is weak. During severe frosts, the ground air layer with subzero temperatures may extend up to least 5–7 m, as follows from the presence of frost injuries at this height. Such frosts rarely occur during the growing season, as compared to weak and medium strong frosts, and, hence, the frequency of frost injuries in the upper parts of tree stems is lower. The frequency of frost injuries at the bases of large roots, where bark is thin, is also low, because they are usually protected from cooling by the litter and plants of the ground vegetation layer.

Available publications provide little information about the distance to which a frost injury in the same layer of annual wood increment may extend along the stem. In our study, a particular injury was usually revealed at only one height (wood samples were taken at 1-m or 0.8-m intervals). The cases of finding the same injury in two samples taken at two heights were rare. Injuries at both 0.2 and 1 m occurred in spruce in 1925 and 1977 and in larch in 1872, 1882, and 1886; at 2 and 3 m, in larch in 1918; and at 3 and 4 m, in spruce in 1945. The most extended injury (dated 1918) appeared in one spruce tree: it was found in samples taken at heights of 0.2, 1, 2, and 3 m. None of the injuries found at the bases of large roots were detected in stem wood, even in the lowest level (0.2 m). Thus, the same frost injury extended along the stem for no more than 1–2 m or, in rare cases, 3–4 m. Similar observations were also made by other authors (Glerum, 1975; Fayle, 1981).

GUIDELINES FOR COLLECTING WOOD SAMPLES

One of the purposes of this study was to draw up guidelines for collecting and preparing wood samples for the analysis and dating of frost injuries.

The most promising regions for such studies are at the arctic and altitudinal limits of tree growth, where frosts occur with a high frequency. Open forests or separate trees are preferable, as they have a weaker influence on microclimate than closed stands. In the absence of open forests, trees from forest margins may be used. Special attention should be devoted to tree stands growing in depressions, which are filled with cold air during frosts.

Frost injuries occur in coniferous and deciduous trees and shrubs. Conifers are more promising because of their longevity and wide distribution in regions with extreme climatic conditions. Introduced species, either coniferous or deciduous, are very sensitive to frosts (Nilov, 1979). Although both species used in our studies are suitable for the study of frost injuries, Siberian larch is inferior to Siberian spruce in this respect. In the extreme north, Siberian juniper is a promising species.

Frost injuries in a thick tree can be found only in the first few tens of rings, which formed when the tree was thin. Hence, to construct the chronology of frosts and analyze their frequency in a certain area, it is necessary to take samples from trees of different diameters, selecting at least 5–10 model trees of each size class. To provide for continuity of the chronology, trees differing in age (as well as in diameter) should be selected.

Wood samples taken from the bases of trees (up to 1 m) are most informative. Crosscuts are preferable, as frost injuries do not necessarily extend throughout the circumference of a tree ring. When tree cutting is inadmissible or impossible, an increment borer may be used. In this case, no less than four radial samples (along two perpendicular axes) should be taken at each height, with each sample containing wood from the pith ring. Samples taken at different heights provide data on frosts of different intensities, which contributes to the accuracy of tree-ring chronology.

An essential condition for reliably revealing frost injuries is that the surface of a sample (crosscut or a core) should be trimmed with a sharp cutting tool. Grinding is not appropriate in this case, because pores are filled with wood dust and small injuries may remain unnoticed. Identification of frost injuries is not associated with major difficulties: their structure has been described in detail, and they differ from other types of damage. Finally, the absolute dating of frost rings by dendrochronological methods is crucial.

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