Russian Journal of Ecology, Vol. 33, No. 4, 2002, pp. 231–234. Translated from Ekologiya, No. 4, 2002, pp. 250–253.

Distribution of Fine Roots of Coniferous Trees over the Soil Profile under Conditions of Pollution by Emissions from a Copper-Smelting Plant

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Received November 13, 2000

Abstract—The distribution of fine conducting roots of Siberian spruce, Siberian fir, and Scotch pine over the soil profile was studied in the taiga ecosystems polluted with heavy metals and SO_2. Under conditions of heavy pollution, tree roots were not found in the forest litter. Regardless of the level of technogenic load, the largest amount of conducting roots concentrated in the upper layer of mineral soil.

Key words: conifers, fine roots, soil pollution, heavy metals.

Comprehensive studies on the responses of various plant parts (both aboveground and underground) are required for gaining an insight into the causes and mechanisms of degradation of forest communities exposed to technogenic impact. However, specific structural features of the root systems of trees growing under such conditions are presently understood substantially less comprehensively than the corresponding responses of aboveground organs (i.e., the photosynthetic, generative, and transport systems). The effects of various pollutants and other technogenic factors were studied under laboratory conditions (Schier, 1985; McQuattie and Schier, 1990; Stavrova, 1990) and in vegetation experiments (Blaschke, 1986; Weiss and Agerer, 1986; Dighton and Skeffington, 1987; Vogelei and Rothe, 1988; Stavrova, 1990). However, it is obvious that such experiments cannot substitute studies performed in the natural environment, which, unfortunately, are quite rare (Kulagin, 1964; Yarmishko, 1984, 1990; Kocourek and Bystřičan, 1989).

In this work, we describe specific structural features of the root systems in edificator coniferous species of the taiga zone (*Abies sibirica* Ledeb., *Picea obovata* Ledeb., and *Pinus silvestris* L.) in natural ecosystems exposed to chemical pollution with emissions from a copper-smelting plant.

STUDY REGION AND METHODS

Field surveys were carried out between July and September 1997 in the area polluted with airborne emissions from the Middle Ural Copper-Smelting Plant (the southern taiga subzone of the Middle Urals near the city of Revda). Dust containing heavy metals (Cd, Cu, Pb, and Zn) and SO_2 was the dominant pollutant. Test plots were laid in spruce–fir forests and pine plantations of age class 2 disturbed to various degrees. All the plots were in the middle parts of flat slopes with gray forest soils.

The frequency of fine conducting roots (less than 3 mm in diameter) in the organogenic horizons was assessed in 20 excavations randomly distributed over the plot, excluding the zones adjoining tree trunks and gaps in the tree stand. The presence of roots in the A1 horizon was also recorded. The distribution of fine tree roots over the soil in forest communities is uniform, random, and independent of the distribution of the aboveground parts of trees (Oya and Lykhmus, 1985). Hence, the frequency of fine roots was used as an index characterizing the expansion of tree roots over the phytocenosis area.

Specific features of the vertical distribution of fine roots were studied in spruce–fir communities using a simplified trench method (Krasil'nikov, 1983) in tree zones located at different distances from the plant: 1 and 2 km (the impact zone), 4.5 and 7 km (the buffer zone), and more than 30 km (the background zone). Soil sections (0.5–0.7 m deep) were cut at a distance of 0.5 m from the trunks of medium-sized fir trees. When the wall of the section dried to a depth of 10 cm and crumbled, the emerging fine roots were counted within its 0.5-m-wide segment. In all cases, only live roots were counted.

The concentrations of Cd, Cu, and Pb were measured in acid extracts of the forest litter (5% HNO_3, extraction for one day) using a Carl Zeiss AAS-3 spectrophotometer. Spectral measurements were made at the Laboratory of Ecological Toxicology, Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences. The level of pollution was

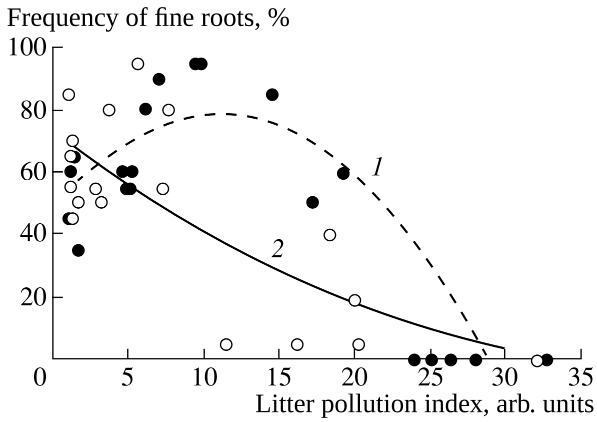

Fig. 1. Frequency of conifer fine roots in the litter as a function of heavy metal concentration in it: (*1*) spruce–fir forests, (*2*) pine forests; the lines show the second-order parabola approximation.

assessed using the index of integral toxic load, which was calculated as the sum of excesses of metal concentrations over the corresponding background levels (Vorobeichik, 1995).

RESULTS

Concentrations of acid-soluble forms of cadmium, lead, and copper in the litter in the areas adjoining the copper-smelting plant exceeded the corresponding background levels by factors of 3–5, 12–18, and 40–60, respectively. The frequency of fine conifer roots in the litter decreased markedly upon an increase in the toxic load. At a high pollution level, the fine roots of trees were virtually absent from the organogenic soil horizons in both pine and dark coniferous communities (Fig. 1). Moreover, the litter in the vicinity of the plant was almost free of the roots of herbaceous plants and dwarf shrubs.

In the background zone, the frequency of fine roots in the litter ranged from 44 to 85% in the pine communities and from 36 to 60% in the dark coniferous communities. The conducting roots proper were usually scarce in organogenic horizons. The litter (1.2–1.5 cm thick) usually contained terminal root endings represented by growth roots and mycorrhizas. Slightly higher indices of root frequency in the litter (62–84%) were observed in the primary and conditionally primary dark coniferous forests of the Middle Urals (the Visim State Nature Reserve).

The highest frequency of fine roots in the litter (up to 100%, averaging 62–93%) was observed in the dark coniferous communities exposed to a moderate technogenic load. The litter in these communities was well developed, 5–7 cm thick, and interlaced by numerous tree roots occurring throughout its thickness, except for the upper subhorizons $A0_T$ and A0'. Root frequency in the litter of moderately polluted pine communities was not increased.

The lowest frequency of fine roots was typical of the thick litter of heavily polluted areas, which consisted of weakly decomposed plant debris. In many test plots of the impact zone, this index decreased nearly to zero, and fine roots were only found at a depth of 10–15 cm. The proportions of such excavations in spruce–fir and pine forests were 62% and 73%, respectively. In some heavily polluted areas, root frequency in the litter was close to that in the background zone.

The range of variation in this parameter between test plots increased as the distance from the plant decreased: variation coefficients under background conditions were 22–23% in both types of communities, compared to 171% in dark coniferous forests and 141% in pine forests in the polluted zone.

The root systems of Siberian fir were used for analyzing the distribution of fine roots throughout the whole soil profile. The results showed that the litter in background and moderately polluted communities contained from 3 to 44% (on average, 8–14%) of the total

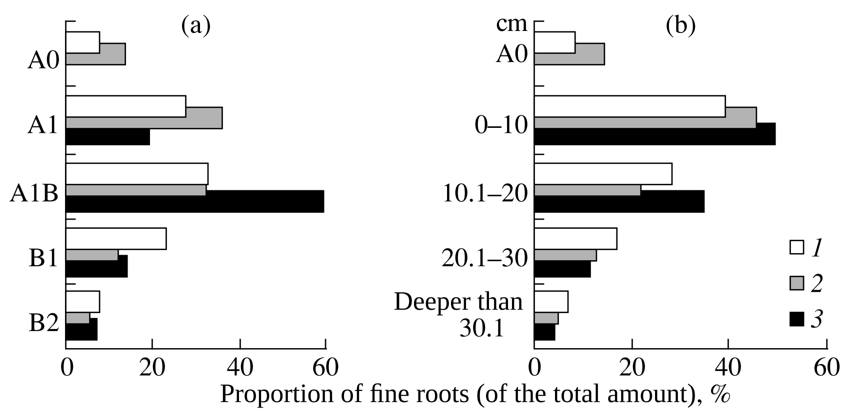

Fig. 2. Distributions of Siberian fir conducting fine roots over (a) soil horizons and (b) 10-cm soil layers in (*1*) background, (*2*) buffer, and (*3*) impact zones of technogenic pollution.

amount of fine roots counted on the wall of a soil section. The litter horizon in areas adjoining the plant contained no conducting roots (Fig. 2a). In these areas, the amount of roots in the humus horizon was slightly smaller, whereas that in the A1B horizon was greater than under background conditions. However, in all areas exposed to the technogenic impact, the largest proportion of fine roots (34–69% of their total amount) was found in the upper 10-cm layer of mineral soil. The number of fine roots in soil sections gradually decreased with an increase in depth (Fig. 2b).

DISCUSSION

The absence of conducting (therefore, absorbing) roots of conifers from the litter in heavily polluted areas is an unusual and atypical situation, which has no natural analogues. The plant species studied in this work, especially dark conifers, are characterized by a surface location of conducting and absorbing roots, which actively invade the organogenic horizons even under extreme growing conditions (Orlov and Koshel'kov, 1971; Abrazhko, 1973; Bobkova, 1987; Nikonov, 1987).

Previously, the deep location of all root fractions and their dying at a high rate in the upper soil layers was described in Scotch pine growing under conditions of pollution with emissions from a metallurgical plant (Yarmishko, 1984, 1990) or the accumulation of magnesite dust in the soil (Kulagin, 1964).

Concentrations of pollutants in the forest litter are usually higher than in the mineral soil (Chertov *et al.*, 1990). The comparison of our data on litter pollution and published data on the levels of soil pollution in the study region (Vorobeichik, 1995) confirms this conclusion. Additional technogenic acidification of the litter (Vorobeichik, 1995) causes an increase in the mobility (toxicity) of metal ions. Therefore, it is most probable that the elimination of fine conducting roots from organogenic horizons in heavily polluted areas is due to extremely high levels of toxicity in these horizons. It is well known that metal ions exert a direct toxic effect on root growth (Schier, 1985; Stavrova, 1990), and this effect is often considered to be responsible for a high rate of tree root dying off in the vicinity of industrial facilities (Yarmishko, 1984, 1990; Kocourek and Bystřičan, 1989). It is also possible that the observed responses of conducting tree roots are explained by the reduced content of the accessible forms of biogenic elements in the technogenic litter (Vorobeichik *et al.*, 1994) or unfavorable water–air characteristics of the latter.

In taiga ecosystems, the litter is a very important depot of biogenic substances (Karpachevskii, 1981; Nikonov, 1987). The active growth of plant roots in the litter is regarded as an adaptation aimed at increasing the rate of biological turnover, preventing the loss of biogenic substances from the ecosystem, and improving their supply to plants (Bobkova, 1987; Nikonov, 1987). In polluted areas, the trees cannot use the litter as a source of mineral elements, and this apparently has an adverse effect on their state. At the level of the ecosystem as a whole, the processes descried above may cause a further decrease in the rate of biological turnover in polluted areas.

ACKNOWLEDGMENTS

I am grateful to Drs. E.L. Vorobeichik and E.Kh. Akhunova, specialists of the Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, for expert assistance in chemical assay.

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