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RESPONSE OF SCOTS PINE (*PINUS SYLVESTRIS* L.), SUKACHYOV'S LARCH (*LARIX SUKACZEWII* DYLIS), AND SILVER BIRCH (*BETULA PENDULA* ROTH) TO MAGNESITE DUST IN SATKINSKY INDUSTRIAL HUB

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Abstract

Deforestation due to air pollution is a serious problem in industrial sites. Aim of this study was to evaluate the impact of magnesite dust on growth of Scots pine (*Pinus sylvestris* L.), Sukachyov's larch (*Larix sukaczewii* Dylis; Syn. *Larix sibirica* Ledeb.) and Silver birch (*Betula pendula* Roth) planted in soil plots between 1980 and 1983 in Satkinsky District, Chelyabinsk. The trees in zones of moderate and low pollution survived, while those in strongly polluted zones died with the exception of Silver birch in soils ameliorated with 12 cm thick peat layer. However, in the zone of strong pollution, coniferous species treated with only 2 cm thick peat layer and weak sulphuric acid solution, grew better than the Silver birch. Twelve centimetres of peat layers could mitigate dust impact on Silver birch, while their 2 cm thickness was not adequate. The dust pollution hit the plants at strongly polluted sites more severely than those at sites with moderate and low pollution. Silver birch and Scots pine trees were more severely impacted by dust pollution compared to Sukachyov's larch trees. Soil remediation is needed in strongly affected areas. While soil remediation is not needed at moderately and low affected sites, these sites should be monitored to avoid their degradation.

Key words: conifers, reforestation, survive, technogenic pollution.

Introduction

Technogenic load is currently considered to be one of the most powerful factors (Ozel et al. 2015) destabilizing forest ecosystems (Isaev and Korovin 1998) and the plantation in urban areas, especially in temperate and boreal zones. The impact of chronic technogenic air pollution near large industrial centres severely affects the plants in these areas; thus, plants cannot fulfil their aesthetic and air-cleaning role. Decreased productivity of pine plantations on anthropogenically damaged forests has been reported in the Republic of Belarus. In that forest, Scots pine (46 %) and Silver birch (30 %) are the prevailing species as a part of natural regeneration, the presence of other species is insignificant (Potapenko 2014).

Plants in industrial centres clean the air, improve the microclimate and keep and inactivate toxic emissions (Grigoriev and Yurgenson 1982). However, long-term air pollution prevents reforestation (Guderian 1979, Smith 1985). It is emphasized that the main problem of applied ecology is to develop a system of parameters to reliably diagnose the initial stages of anthropogenic transformation of ecosystems and critical conditions of their dynamics. It is closely connected with questions of setting ecological standards for anthropogenic loads. Many studies have been carried out on technogenic pollutions (Guderian 1979, Smith 1985, Burton 1986). The Satkinsky District, Chelyabinsk is such a highly polluted area.

The main air pollutant in this area is the magnesite dust, which is highly alkaline (approximate pH 10) and mostly comprises magnesium oxide that breaks down to form $Mg(OH)_2$. The pollution in this area is thus alkaline. Previous studies have been conducted on magnesite pollution (Zavyalov and Menshikov 2009), elevated phytomass (Zavyalov and Menshikov 2010), the morphological and chemical composition of leaves of pilot plantations (*Betula pendula* Roth) (Zavyalov 2013), reproduction (Mohnachev et al. 2013, Mohnachev 2014), quality of seeds and seed posterities (Makhniova et al. 2013, Makhniova and Mohnachev 2014) of pilot plantations (*Pinus silvestris* L). These studies suggested the need for reforestation by cultivating pollution-resistant species.

The aims of this research were i) to evaluate the response of Scots pine (*Pinus sylvestris* L.), Sukachyov's larch (*Larix sukaczewii* Dylis; Synonym of *Larix sibirica* Ledeb.), and Silver birch (*Betula pendula* Roth) woody plants, exposed to different levels of magnesite dust and ii) evaluate the effect of peat thickness in mitigating impact of magnesite dust on the Scots pine, Sukachyov's larch, and Silver birch.

Material and Methods

The research area is near the town of Satka, Chelyabinsk Region, Russia (55°04'N, 59°03'E) (figs 1 and 2). The area of Satka is located in the central sub-belt of the southern boreal forests of South Ural (Kolesnikov 1969). The study area comprises experimental sites (ES) comprising polluted zones at different degree; one highly polluted zone (ES No 2), two moderately polluted zones (ES No 5–6), one low polluted zone (ES No 3) and one slightly polluted zone (ES No 4, conditionally controlled site) (Menshikov 1985).

All experimental sites have similar plant species and vegetation conditions, except the sites ES 3 and ES 6 where soil fertility is better than the others.

Two and 12 cm thick peat layers were mixed with nitrogen–phosphorus–potassium (NPK) fertilizers and diluted sulphuric acid solution to decrease pH of ES2. Ploughed soil of ES 2–4 and 5–6 were milled and mixed (Menshikov 1985). All surveyed sites are situated northeast of the source of emissions and along the main path of the dust.

The breast diameters of trees (DBH) on experimental site were measured with an accuracy of 0.1 cm. The height of the trees was measured with a Haglof altimeter with an accuracy of 0.20. The comparisons were made by F-test for the height and the breast diameter obtained from the treatments. The visual assessment of the extent of air pollution was carried out according by technique (Anonymous 1994). In each tree, the defoliation of the crown and its current state were recorded and damage of the forest stand was charac-

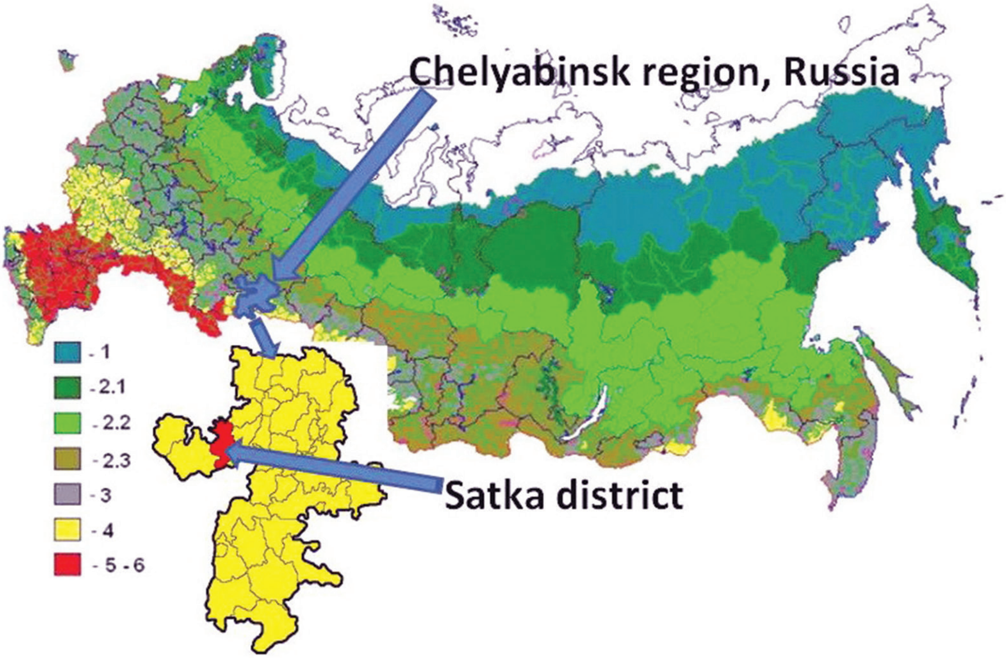

Fig. 1. Location of the study area.

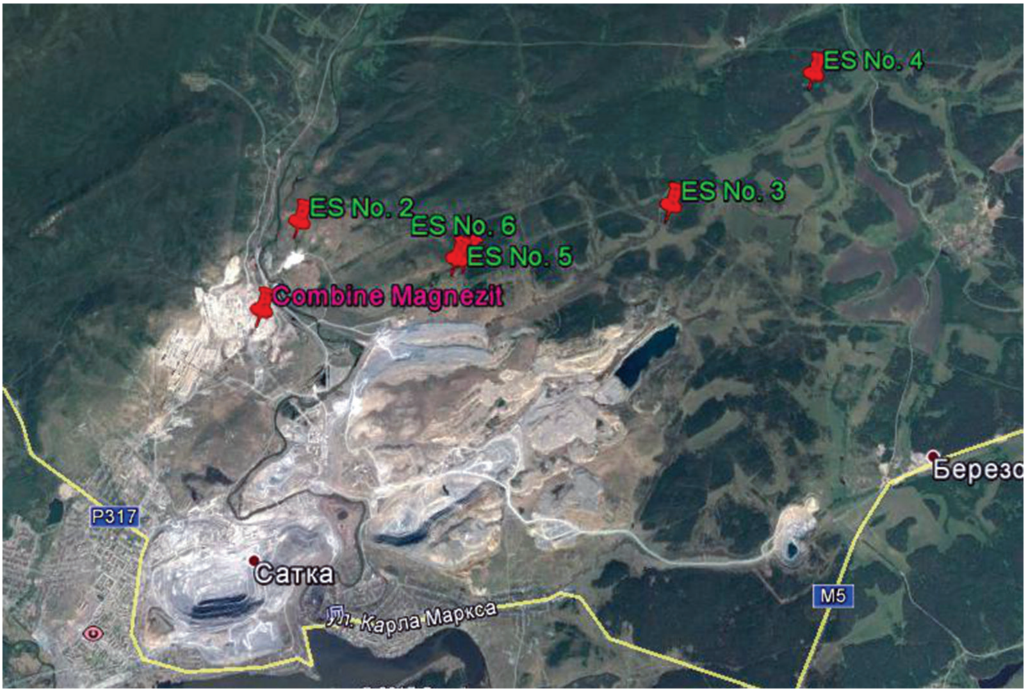

Fig. 2. Location of experimental sites and Combine Magnezit.

terized after Menshikov (2001) (Table 1).

Table 1. Scale used in determination of tree defoliation in different damage groups (Menshikov 2001).

Damage	Mean defoliation, %
Background	0–20
Low	21–40
Average	41–60
Heavy	61–99

Integral classes based on the account of morphological bio-indication signs of tree damage were used to assess the vital state of the stand. As a result of forest pathological research, a system of correct and objective criteria was developed, such as the status category, damage classes, life scores (Menschikov 2001).

The status of trees can be defined in six classes:

1. Background (without signs of damage). Degree of defoliation is 0–20 %.
2. Low. The degree of defoliation is 21–40 %. The life span of pine needles is reduced by 20–30 %.
3. Average. The degree of defoliation is 41–60 %. The life span of pine needles is reduced by 31–50 %.
4. Heavy. Degree of defoliation is 61–99 %. The life span of pine needles is reduced by 50–75 %.

The index of damage to the stand on the site was calculated as the average of the categories (classes, points) of the state of 100 to 120 main-tree trees counted on the experimental site.

Equation (1) was used in the calculation:

$$Ip = \frac{n_1K_1 + n_2K_2 + ... + n_6K_6}{N} \qquad (1),$$

where:

n_{1-6} is number of trees I, I–IV category (damage classes);

K_{1-6} – the points of the living condition of the categories of trees corresponding to the category number (damage class);

N – the total number of recorded trees on the sample area.

In mixed stands, the damage index was determined separately for each breed. Then a general index was calculated, the average for each of them.

The life expectancy of the pine needles was made by a visual estimate of the shoots, based on the number of interned internodes. Escape from the fully preserved needles is taken equal to unity, with a partially preserved one – to the tenth parts of the unit. The age limit was determined by summing all the values. Observations were made on 15–20 tree shoots in the upper third of the crown (Gruber 1988).

Results

The trees in moderately and low polluted zones had survived for 30 years, whereas those in strongly polluted zones died, with the exception of Silver birch in soils with 12 cm thick peat layers (Fig. 3).

Peat layers of 12 cm thickness, fertilizer NPK, a low acid solution (H_2SO_4) were added to the soils prior to planting of Silver birch, Scots pine, and Sukachyov's larch in the strongly and low polluted zones (Fig. 4). For Silver birch was another variant with a peat layer 12 cm. This is done primarily to acidify the soil.

The tree growth suggests that the mean diameter of the Silver birch in soils with the 12 cm thick peat layers is not significantly different compared to the diameter of the larch in soils treated with acid and that of the Scots pine in soils with 2 cm thick peat layers, while the mean height of the Silver birch trees is 43 % and

Fig. 3. Silver birch in strongly polluted soils treated with 12 cm thick peat layers.

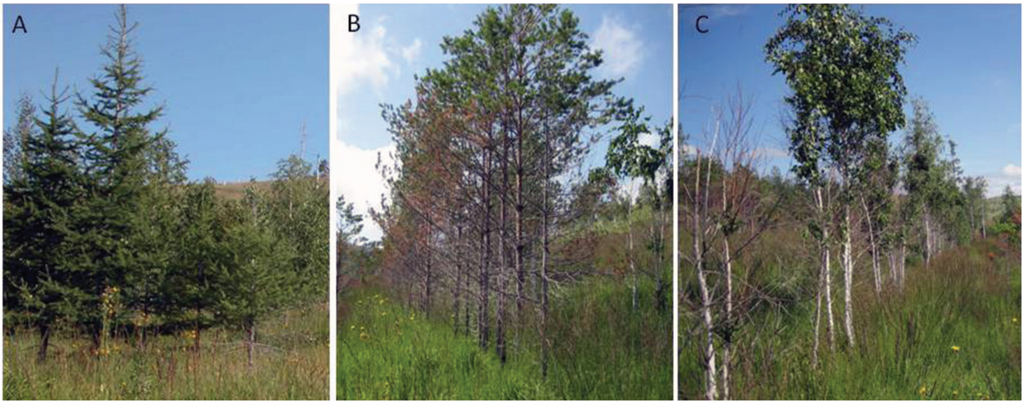

Fig. 4. The experimental plots in the strongly polluted zone: A) Sukachyov's larch in soils treated with diluted H_2SO_4 solution; B) Scots pine in soils treated with 2 cm thick peat layer; C) Silver birch in soils treated with 2 cm thick peat layer.

29 % higher than those of Scots pine and Sukachyov's larch, respectively ($F = 3.99$ and $F = 3.67$ with $p < 0.001$) (figs 5 and 6).

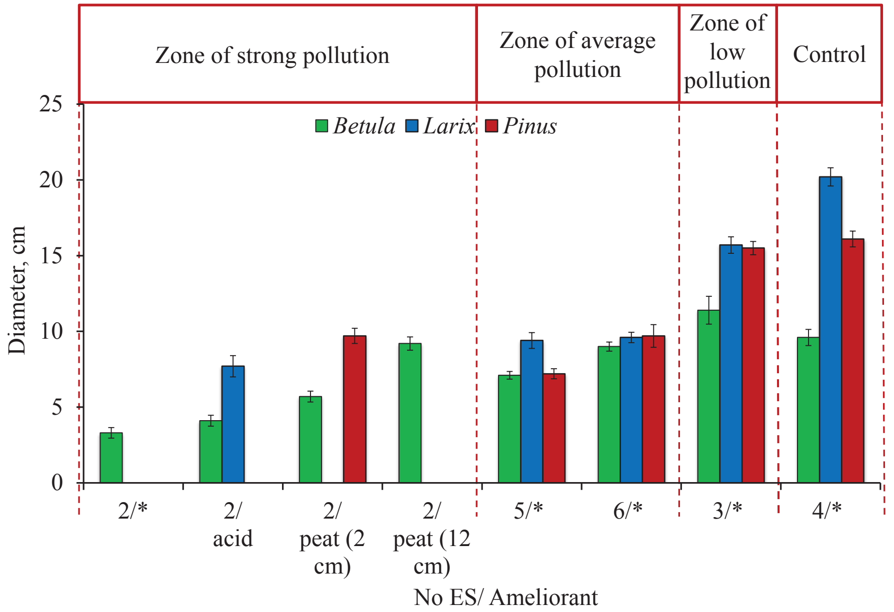

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Fig. 5. Mean breast diameter of trees at the different experimental sites.

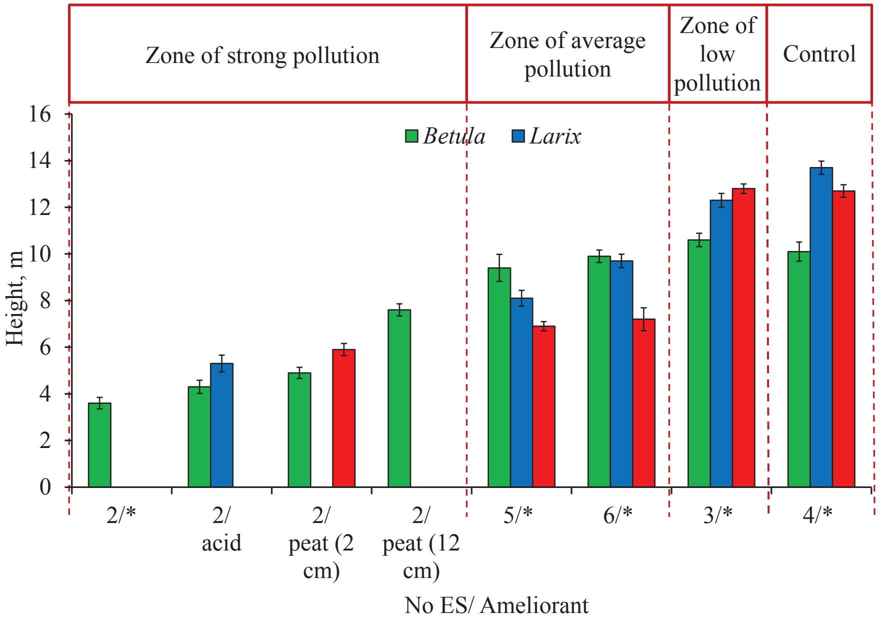

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Fig. 6. Mean tree height at the different experimental sites average pollution.

Silver birch individuals survived only in soils with the 12 cm thick peat layers. The breast diameter of the stem increased 2.8 times ($F = 9.23$, $p < 0.001$) and the tree height increased 2.1 times ($F = 10.2$, $p < 0.001$). Silver birch and Scots pine data in soils with 2 cm thick peat layers suggest that the height and diameter of the pine individuals was 20 % ($F = 2.46$, $p = 0.02$) and 70 % higher ($F = 6.34$, $p < 0.001$) than those in the Silver birch individuals. The larch individuals in soil treated with the acid solution show increased growth compared with birch; the breast diameter is 88 % ($F = 4.75$, $p < 0.001$) and the height is 23 % higher ($F = 1.89$, $p = 0.06$). However, the larch individuals had smaller (26 %) diameter than the Scots pine ($F = 2.40$, $p = 0.02$). In the zone of strong pollution, the coniferous species grew better than the birch.

In the moderately polluted zone (ES 5), larch individuals showed the largest increase in the breast diameter; that is 32 % and 31 % higher than that of the birch and pine ($F = 4.23$, $F = 3.48$, $p < 0.001$), respectively. However, the differences in height among the different tree species are not significant in this zone.

In the zone of low pollution, the growth rate of larch individuals was higher than the Silver birch. The breast diameter of the former was 38 % higher than that of the later ($F = 3.81$, $p < 0.001$) and the height of the larch individuals was 16 % ($F = 4.01$, $p < 0.001$). In this zone, larch and Scots pine trees do not differ significantly in growth rate. At the control site, larch individuals grew most rapidly. Their diameter is 2.1 times thicker than that of the Silver birch ($F = 13.14$, $p < 0.001$) and 25 % thicker than that of Scots pine ($F = 5.06$, $p < 0.001$). The height of the Sukachyov's larch trees is 36 % higher than that of the Silver birch ($F = 7.10$, $p < 0.001$) but it is not different from that of the Scots pine individuals. Apparently, magnesite dust pollution did not hinder the growth of larch, but Silver birch and Scots pine trees.

The data suggest that air pollution resulted in all tree growth indicators to decrease in the ESs. In strongly polluted zone, the mean height of the Silver birch trees growth in the soil with 12 cm thick peat layer is 25 % lower ($F = 4.71$, $p < 0.001$) than that of the Silver birch trees at the control site, while their diameters were highly similar. However, mean diameter and height of the birch trees growth in soils with 2 cm thick peat layers were smaller than those in the same species at the control site (41 % and 51 %, respectively) ($F = 4.68$ and $F = 8.21$, $p < 0.001$) in the strongly polluted zone. For the Scots pine, in the same zone and soils, the diameter and height were 40 % and 54 % ($F = 5.77$ and $F = 11.84$, $p < 0.001$) smaller than those at the control site, respectively The diameter and height of the Silver birch trees in soils treated with acid solution in the strongly polluted zone are 20 % lower than the same species at the control site ($F = 1.67$, $p = 0.10$ and $F = 1.88$, $p = 0.06$), and smaller than the Sukachyov's larch trees (87 % and 23 %, respectively) ($F = 4.75$, $p < 0.001$ and $F = 1.89$, $p = 0.06$) in the strongly polluted zone. Clearly, tree growth is negatively affected by magnesite dust. Furthermore, the use of 12 cm thick peat layers in the soils mitigates the pollution impact on woody plant growth more than use of 2 cm thick peat layers.

Air pollution resulted in increased defoliation and decreased tree growth. Trees, closer to the source of emissions, are damaged most severely. In the zone of strong pollution, the pollution impacted Silver birch trees in soils without ameliorants 2.9 times and Scots pines in soils with 2 cm peat layers 3.2 times of those at control site. Sukachyov's larch trees are impacted in relatively lesser degree, 90 % more than those at the control site (Fig. 7).

In the strongly polluted zone, the pollution increased defoliation of pine trees by sevenfold and that of the birch trees fivefold, compared to those of same species at the control site (Fig. 8). Larch trees are observed to be the least and Scots pine trees the most damaged. The addition of peat to the soil mitigated the impact on the Silver birch. For example, the defoliation of birch in soils with 12-cm peat layers was 20 % less than that in soils without peat.

The amount of defoliation allows grouping the experimental plantations in Fig. 8. In the zone of strong pollution, Scots pine is heavily impacted, whereas birch trees are impacted moderately. In the zone of moderate pollution, Scots pine trees are into the moderately impacted group, whereas Silver birch trees are in the weakly impacted group. In the low pollution and control zones, these pine and birch species are into the background impacted group.

With increasing pollution, the lifespan of Scots pine needles is reduced by 40 % in comparison with the same species at the control site (Fig. 9).

Discussion and Conclusions

Relationship between soil and plants, under the influence of the accumulated aerial technogenic impact of emissions in areas of pollution, has been studied comprehensively for a long time. Snow water

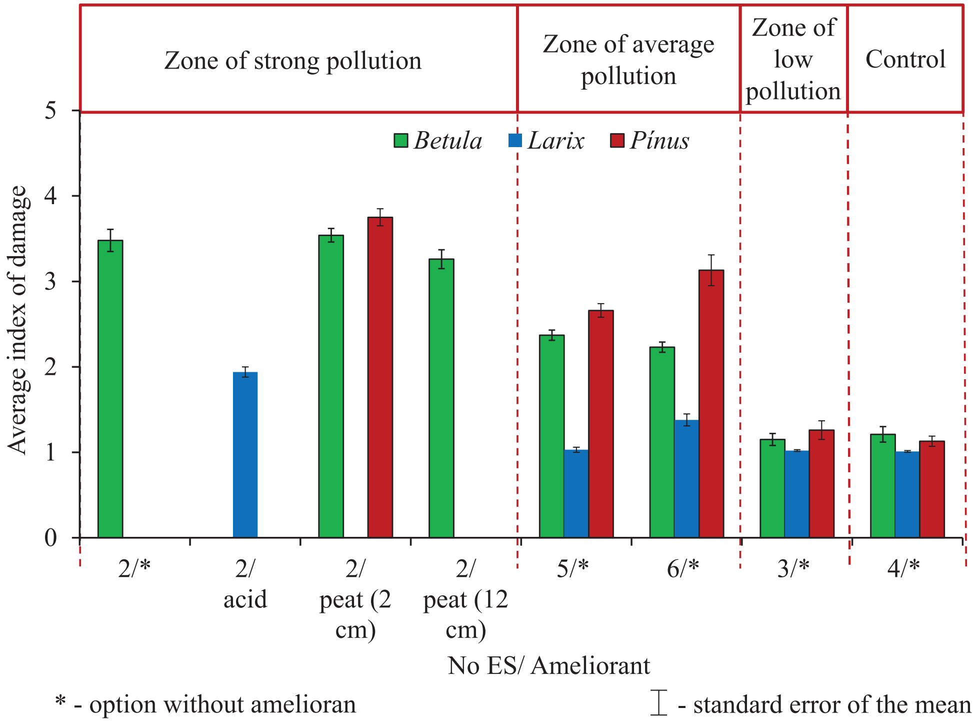

Fig. 7. Mean tree damage at different pollution zones.

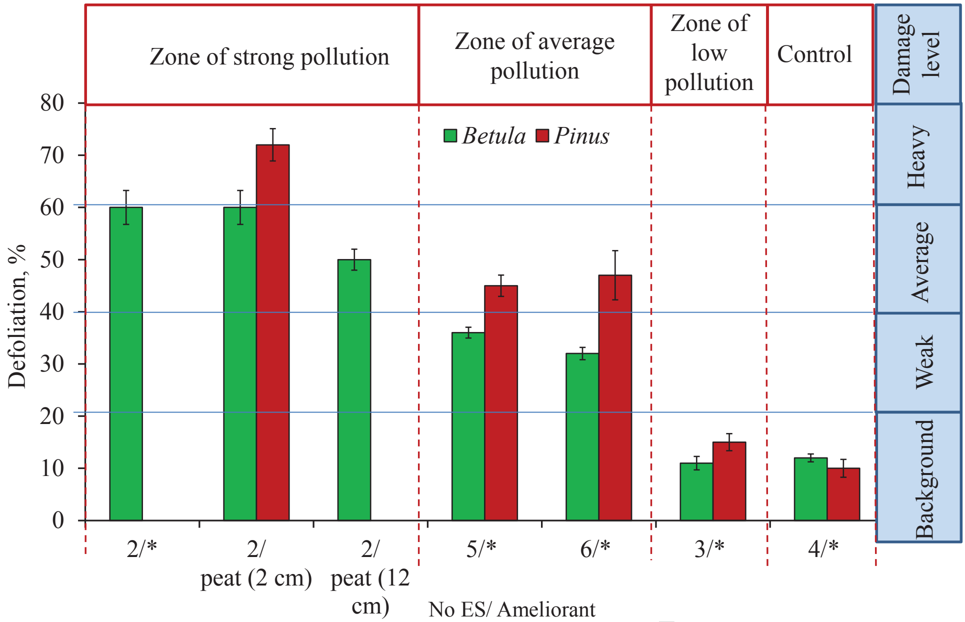

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Fig. 8. Average defoliation in the different zones of pollution.

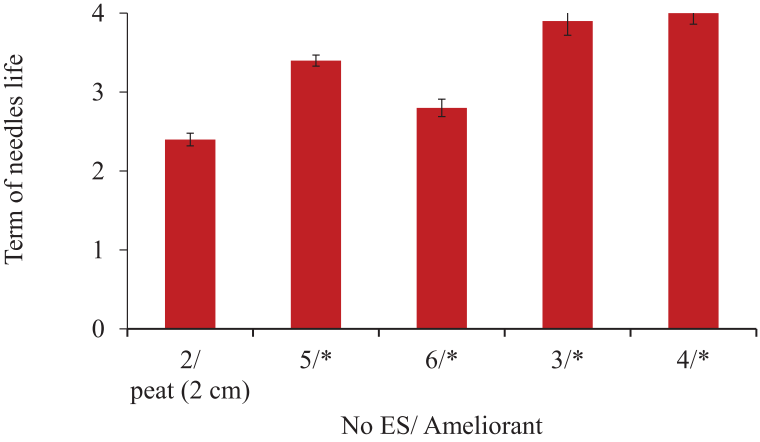

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Fig. 9. Lifespan of the Scots pine needles as affected by rate of ameliorant.

is often used as an indicator of pollution at sites where snow cover stays for long winter period (6–8 months). Our study shows that snow water in the strongly (1 km from the source of exposure) impacted forest areas had suspended solids almost 15 times higher than those in low (10 from the source of exposure) impacted ones for 2012–2014 (Fig. 10).

The content of pollutants reaching up to 30 g/m^2 in the solid fraction (suspended solids) which caused strong destruction of the forest was due to the maximum pollution of air with particulate matter and mineralization of the snow cover.

The snow water was strongly alkaline due to strongly alkaline dust (pH > 10.0) deposited in the snow. The mean values of pH were between 9 and 9.5 in strongly polluted zones in 2012–2013 and was 8.9 in the low affected zones in 2014 (Fig. 11).

During the examination of the soil in areas of the Combine Magnezit (Table 2), a decrease of 0.2–0.6 was found in the pH level of the soil in the upper horizons of moderate and low impacted zones, while almost no pH decrease was observed on strongly polluted soils. Restoration of the polluted soils in this zone is extremely slow, even with a decrease or complete cessation of emissions due to low mobility of most metals in alkaline medium (Kuzmina and Menshikov 2015). Recovery of soils in areas of moderate and low contamination may occur more rapidly if the Combine Magnesite will reduce the volume of gaseous emissions (vapors of alkalis, sulphur dioxide and fluoride).

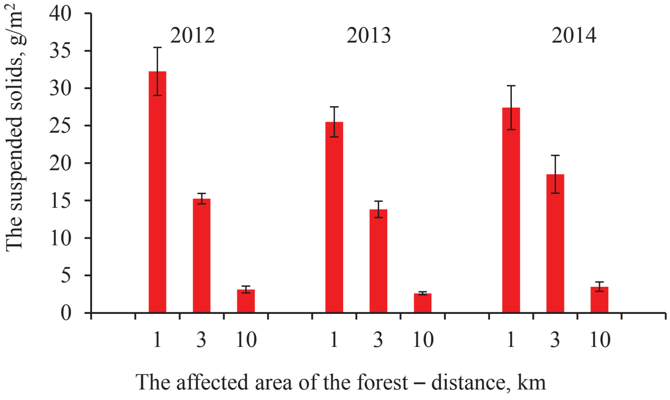

Fig. 10. Dynamics of suspended solids in snow water.

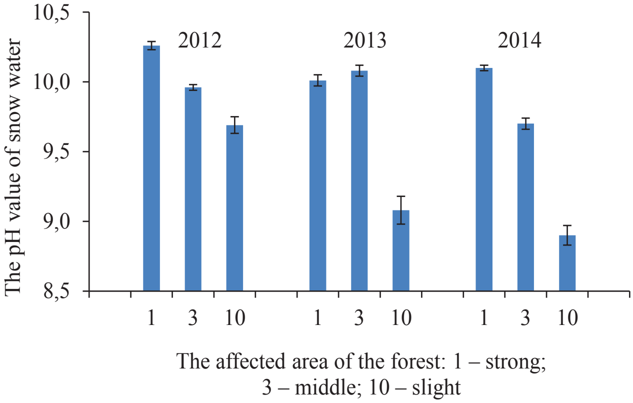

Fig. 11. pH of the snow water filtrates at strongly (1), moderately (3), and slight (10) affected sites in 2012–2014.

Our research showed that natural ratio among the elements in the soil adsorbents was disrupted in 1983, indicating that the magnesium was the principal exchangeable element at the soil adsorbents in strongly polluted soils (Fig. 12), and calcium in slightly polluted ones. However, the ratio of exchangeable cations changed in favor of calcium in strongly polluted soils in 2013.

Table 2. Soil pH in different zones of magnesite contamination in the upper (0–10 cm) soil layer in different years.

Severity of pollution	**Distance from the emission source, km**	**Soil type**	**pH (H_2O) soil by years**				
			1983*	**1990**	**2005**	**2008**	**2010**
Strong (ES No 2)	1	Gray soils, light loamy	9.1	8.2	8.9	8.7	8.9
Moderate (ES No 5)	3	Gray soils, medium loamy	8.9	8.0	8.5	8.0	8.3
Moderate (ES No 6)	3.5	Dark gray soils, medium loamy	8.2	no data			7.8
Low (ES No 3)	5	Dark gray soils, light loamy	7.9	7.3	7.4	7.5	7.6
Slight (ES No 4, conditionally controlled site)	10	Gray soils, light loamy	7.7	7.0	7.6	7.2	7.3

Note: *Data are from Menshikov et al. (1987).

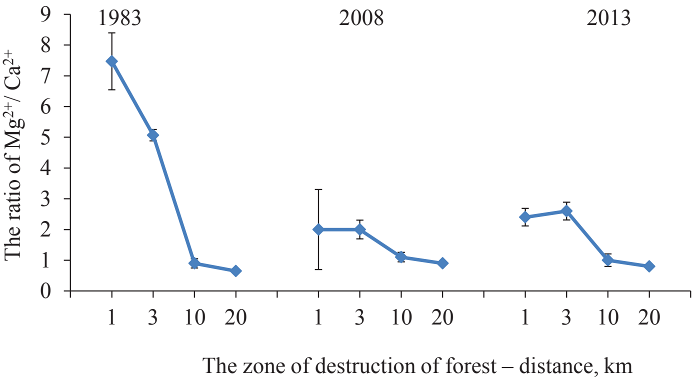

Fig. 12. Ratios of exchangeable Mg^{2+} to Ca^{2+} in soil of strongly (1), moderately (3), slightly (10) polluted and control (20) sites in 1983*, 2008 and 2013.

Note: *Data are from Menshikov et al. (1987).

We observed that reduction of solid emissions of the Combine Magnezit resulted in a partial recovery of soils in 30-year period as Mg and Ca ratio in the emissions decreased, resulting in reduced amounts of Mg accumulations in soils.

Scots pine, a widely distributed pioneer and important forest-forming tree, is characterized by high sensitivity to technogenic polluting agents (Mikhailova 2000). High correlation has been found between levels of SO_2, HF, and aerosols with heavy metals in polluted atmospheric air and accumulation of related elements such as sulphur, fluorine, lead, cadmium, mercury, etc. in pine needles (Mikhailova et al. 2003). Sazonova and Olchev (2010) emphasized that comparisons of the responses of *Picea obovata* Ledeb. and *Pinus sylvestris* L. trees to industrial pollution showed that a relationship between tree vitality statuses shown by visual traits and by physiological criteria was more evident for *P. obovata* than *P. sylvestris* trees. It can be expected that at the same pollution level, the life span of pollution exposed Siberian spruce would be shorter than that of the Scots pine trees at the same pollution level. Thus, spruce may be less resistant to pollution than pine trees. Decreased pH generally results in increased migration of pollutants from the soils. In parallel, revealed an increase of sulphur, fluoride, heavy metals in the tissues of woody plants (twigs, leaves) (Mikhailova et al. 2015).

Sulphur and lead make complexes with exchangeable calcium, magnesium, potassium, and sodium in soils, therefore, is reducing their availability for root uptake by plants (Mikhailova et al. 2007, 2015). Biogeochemical disturbances in forest ecosystems ultimately lead to changes in the nutrient status of major producers (woody plants) and reductions in their morphostructural parameters and overall growth characteristics (Mikhailova and Shergina 2011, Trowbridge and Bassuk 2004).

There are two points of view on the response of plants to elevated levels of magnesium in soils. Ions of magnesium carbonate have the same impact on the growth and development of plants as ions of soluble salts (Gedroits 1935). Altered nutrient flow affects magnesium ratio in plant cells, as well as the lack of a vegetative organism some other items. The result is a poorly developed root system in such soils. A reduction of bio-ecological quality of trees growing on soils containing more cations of magnesium was found – one grade lower (Rzhannikova 1972).

Excess calcium and magnesium and the ratio between them have little effect on the growth of pine trees, but have an indirect impact, shifting the pH to the alkaline side. At pH above 8 iron compounds are in the form of insoluble hydroxides and plants can't use them (Wozbudskya 1964). Plant availability of P, Mn, Zn, Fe, Cu, B, and N is decreased as pH increases (Pokhlebkina and Ignatov 1983). The content of exchangeable magnesium in 36 % dramatically enhances the toxic effect in the soil, providing strong soil salinity caused by sodium (Orlovsky 1979). In this regard, the soil takes on the properties of alkalinity, becomes viscous, structureless. It is known that the exchange of magnesium is one of the main cations, and its availability depends on the cation-exchange capacity of the soil and the influence of competing cations Ca^{2+}, K^{+}, NH_4^{+}, Fe^{2+}, Al^{3+}. In addition, increased Mg concentration in the nutrient medium reduces the plant uptake of competing cations, primarily potassium and calcium.

Magnesite dust pollution impacted birch and Scots pine more than larch. The addition of 12 cm thick peat layers to the soil mitigated the effect of high air pollution and fosters tree growth. In moderately and low polluted sites, tree growth is affected less and soil does not require treatment.

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