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Morphophysiologic Traits of Spruce Trees in Conditions of Izhevsk

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Abstract—Data on the condition of *Picea* genus (spruce) representatives in an urban environment have been analyzed. The viability under different environmental conditions and stand types is evaluated. The relative viability of forest stands is evaluated. Morphogenic traits of conifers are examined for the annual increment development. The photosynthetic pigments dynamics is tracked for two coniferous plants across various forest types, including park forests, roadside hedgerows, and plantings in the residential area. The specific responses of pigment system to the urban environment have been revealed for the two coniferous plant species. We have found an increased concentration of carotinoids and higher resilience of blue spruce (*Picea pungens* Engelm.) in an urban environment.

Keywords: Blue spruce, Norway spruce, adaptation, resilience, urban ecosystem, photosynthetic pigment, plant growth and development, tannin

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INTRODUCTION

Environmental pollution is an urgent problem, especially in urban and industrial areas. Exposure to toxins leads to a significant deterioration and even death of plants over vast areas.

Arboreous plants are widely used in landscaping cities as an important environmental changing factor. They absorb and neutralize a part of atmospheric pollutants and retain dust particles, reducing the level of the harmful effects of toxicants in the surrounding area (Kulagin and Shagieva, 2005; Bukharina et al., 2007, 2012). Currently, conifers, among which there are highly decorative and resilient species, are not sufficiently used in landscaping cities (Voskresenskaya, 2006; Bukharina, 2013).

Studies of arboreous plants in Izhevsk city have been carried out since 2000, but mainly in terms of hardwoods and plant species dominating in the grass cover. Some indicators of conifers, showing a good vital condition of barbed spruce (*Picea pungens* Engelm.) in urban plantings, were investigated in some areas of the city. The authors pointed to the need of studying the characteristics of the adaptation of the species in urban environment (Bukharina and Povarnitsina, 2013).

Biochemical properties; physiological processes; and, as a consequence, plant morphostructure change under conditions of environmental pollution in a city. It is known that the degree of plant damage depends mainly on two factors—the concentration of the toxic substance and the duration of its action (Kovalsky, 1974; Kurbatova et al., 2004; Bukharina et al., 2007).

Photosynthesis is very sensitive to environmental factors and is closely related to the physiological age of the leaves and the plant state as a whole (Neverova and Kolmogorova, 2003). Dust and soot in the air are the factors that reduce the photosynthetic activity of arboreous plants under conditions of atmospheric pollution; their action is manifested in the plugging of the stomata, delayed the absorption of CO_2, and changing in the optical properties and the thermal balance of the leaves (Veretennikov, 1980; Chernishenko, 2001).

The ability to increase the synthesis of carbon-containing compounds (pigments, lignin, wax, phenols, tannins, etc.) in the assimilation apparatus is one of the factors for the resilience of plant organism to stress. These substances can reduce the intensity of environmental factors and prevent the loss of moisture in plant leaves during drying and freezing, as well as the action of ultraviolet radiation (Ivanov, 2001; Troshkova and Vinokurova, 2005; Fuksman et al., 2005). Tannins are one of these substances.

Tannins are accumulated in vacuoles and adsorbed on cell walls in the aging cells. The mixture of hydrolyzed and condensed tannins with a predominance of compounds from one or another group is most often found in plants. The content of tannins in plants varies, depending on the growing season and the plant age. Their accumulation is accompanied by a sharp increase in the mass of root systems. The content of tannins decreases in aging plants. The vegetation period influences not only quantitative, but also the qualitative structure of tannins. Plants growing in the sun accumulate more tannins than those growing in the shade (e.g., tropical plants produce significantly more tannins than the plants of temperate latitudes). The content of tannins depends on climate, soil conditions, and genetic (hereditary) features of a plant. Having bactericidal properties due to its phenolic nature, tannins prevent wood rotting and are substances that protect plants from pests and pathogens. Tannins are also involved in plant metabolism; they are accumulated as a storage substances, which can be used later during the spring awakening and progressive increase in vegetative organs (Karpuk, 2011). It is thought that tannins can form compounds with heavy metals and, therefore, their content may indirectly show the content of heavy metals in plants (Kretovich, 1986).

The aim of our research was to study the ecological and biological characteristics and adaptive reactions of the representatives of *Picea* genus under urban conditions for reconstructing and creating urban plantings using the example of the city of Izhevsk.

The relevance of research is associated with the need to identify the responses of coniferous species on the conditions of urbanized environment and to define important physiological, biochemical, and morphological parameters of plant response to man-made pollution and indicator parameters suitable for selecting species that are resistant to the urban environment.

MATERIALS AND METHODS

Coniferous species were studied in the plantings of Izhevsk, the central part of Udmurt Republic (56°50′59″ N, 53°12′16″ E) (Ilminskikh, 1998).

The city is confined to the eastern outskirts of the Russian platform, the relief is a hilly plain, and the basic soil type is sod–podzolic. Izhevsk is located on the border of two subzones of the forest zone—southern taiga and mixed coniferous–deciduous forests of the European part of Russia. The climate is characterized as temperate continental with long snowy winter. Southwesterly winds with an average speed of 4 m/s dominate throughout the year. The average annual temperature is 2.4°C and the deviation in different years is usually low. Izhevsk is located in the zone of sufficient moisture. Annual rainfall averages 508 mm, but there is some instability of moisturizing due to the uneven distribution of rainfall by months.

According to the Udmurt Center for Hydrometeorology and Environmental Monitoring, the level of air pollution in Izhevsk is below the national average. In recent years (2003–2013), there has been a tendency toward a reduction in the level of air pollution by sulfur dioxide, carbon monoxide, and nitrogen dioxide. The content of suspended substances, phenol, nitrous oxide, hydrogen sulfide, and formaldehyde in the atmosphere remains consistently low, and the content of benzo(a)pyrene remains stably high. The comprehensive air-pollution index is 6.1. Formaldehyde, benzo(a)pyrene, nitrogen dioxide, phenol, and carbon monoxide are among the major pollutants. The main source of urban atmospheric pollution is motor vehicles, whose total emission of pollutants is 84.5% of all emissions (Koval'chuk et al., 2014).

Taking into account the functional zoning of the city, plantings of different environmental categories subjected to anthropogenic load of varying intensity were selected: plantings in residential areas (Sever residential community (RC Sever)) and roadside hedgerows (Udmurtskaya street). The Kirov central landscape park was selected as a conditional control zone (CCZ) (Krasnoshchekova, 1987).

Some species of coniferous plants were the objects of the study: a representative of the local flora Norway spruce (*Picea abies* L.) and barbed spruce (*Picea pungens* Engelm), an introduced species.

Two to five square test plots (not less than 0.25 ha) were laid in each test planting, within which taxation descriptions of arboreous plants carried out according to (Sokolov, 1998), counting barrel defects (*GOST*..., 1982). The living condition of arboreous plants and the relative vital state of the stand (RVS) was established according to (Alekseev, 1990):

$$\mathrm{RVS} = \frac{100N_1 + 70N_2 + 40N_3 + 5N_4}{n},$$

where N_1, N_2, N_3, and N_4 are the numbers of healthy, weakened, severely weakened, and dying trees in the plot, respectively; 100, 70, 40, and 5 are coefficients expressing (in percentage) the living condition of healthy, weakened, severely weakened, and dying trees; n is the total number of trees per plot (including dead wood).

A tree stand with a value of the relative vital state from 100 to 80% was evaluated as healthy, from 79 to 50% was weakened, from 49 to 20% was severely weakened, and 19% and below was completely destroyed.

Three model individuals of each species in a good vital state and average generative ontogenetic state were selected to study the physiological and biochemical parameters in the test plots.

Soils in the test plots were taken as mixed samples. The following indicators were identified to study the agrochemical properties of the soil: $\mathrm{pH_{KCl}}$ (*GOST*..., 1987); $\mathrm{pH_{H_2O}}$ (*GOST*..., 1984); the content of organic matter (humus) (%) according to the method of I.V. Tyurin modified by V.N. Simakov; the content of ammonium nitrogen (photocolorimetry), nitrates (potentiometrically), and mobile forms of potassium and phosphorus (mg kg^{-1} of soil) according to the method of A.T. Kirsanov modified by the Central Institute of Agriculture Agrochemical Service (Yagodin et al., 1987; Kuznetsov, 1994).

Table 1. Agrochemical indices of soil in studied plots

Sampling site	K_2O, mg kg^{-1}	P_2O_5, mg kg^{-1}	NO_3^-, mg kg^{-1}	pH_{KCl}	pH_{H_2O}	NH_4^+, mg kg^{-1}	Humus, %
Kirov Park	371.4 ± 1.3 366.0...376.8	290.8 ± 10.4 246.0...335.5	16.8 ± 0.4 15.1...18.5	5.8 ± 0.2 4.9...6.8	6.7 ± 0.0	331.6 ± 6.9 301.9...361.2	4.2 ± 0.2 3.5...5.0
RC Sever	197.0 ± 3.4 182.4...211.7	133.0 ± 0.0	0.23 ± 0.03 0.09...0.38	7.2 ± 0.0	7.7 ± 0.1 7.6...7.8	108.5 ± 7.4 76.8...140.2	6.5 ± 0.1 6.3...6.7
ul. Udmurtskaya	423.2 ± 9.3 383.4...463.0	321.9 ± 6.9 292.5...351.5	5.1 ± 0.9 1.5...8.8	7.0 ± 0.1 6.5...7.4	8.0 ± 0.3 6.6...9.5	542.0 ± 4.3 480.6...603.4	2.3 ± 0.1 2.1...2.5

The top line in the Tables 1 and 2 shows the average value of the indicator ± standard deviation; the bottom line shows the confidence interval for the mean value.

The vertical increment of annual shoots of 2011 and 2012, selected on the southern exposure of the crown (ten samples from each model plant) was studied in order to evaluate the growth processes. The following morphological characteristics of a shoot were determined: length (cm), number of needles (pcs.), and raw and air-dry mass of needles (g). The area of needles was determined by the formula

$$s = 2L\sqrt{A^2 + B_2},$$

where L is the length of the needles, A is the width of the needles, and B is needle thickness (cited (Karasev, 2001)).

The assimilation activity was studied by quantifying the photosynthetic pigments (chlorophylls A, B, and carotenoids) in the needles of plants on an SF-200 spectrophotometer, measuring the optical density of an alcoholic extract of pigments. The content of the pigments was determined by calculation (Gavrilenko and Zhigalov, 2003). Indicators were studied in dynamics during the growing season; the needles of 2012 and 2013 were used for the analyzes. The content of tannins in the roots of conifers was quantified permanganometrically. Analyses were performed three times. Assays were carried out in the laboratory of ecological safety in Udmurt State University.

The mathematical processing was carried out using the Statistica 6.0 statistical software package. Obtained data were interpreted using the method of principal components, methods of descriptive statistics, and multivariate variance analysis with the subsequent assessment of differences by LSD test. Significant differences between the traits (with $p < 0.05$) were used, comparing and analyzing the results.

Kirov Park is located on the northern outskirts of the city and is an urban landscape park with an area of 85 ha, having a compact undifferentiated configuration. The original forest in the plantings of the park was a wood sorrel spruce forest and cowberry pine forest; however, the indicator plants and immoral grasses typical for these forest types are practically absent because of the high recreational load. Forest pest state of plantings is estimated at 3 points and confined to the massive reproduction of primary (bark beetle) and secondary (borers) xylophagous pests.

Sandy sod–podzolic soils with a neutral acidity and a high content of organic matter (humus) (4%), mobile phosphorus (291 mg kg^{-1} of soil), and exchangeable potassium (371 mg kg^{-1} of soil) dominate in the park (Table 1).

RC Sever is located in the northwestern part of Izhevsk, away from the functioning of industrial enterprises. The residential area is characterized by good transport accessibility; the presence of major transport arteries; high-density residential development; and a large number of office buildings, schools, and kindergartens.

Soils are deeply converted urbanozem with a depth of conversion of more than 50 cm. The acidity of the soil is slightly alkaline, closer to neutral. The content of potassium in the soils is high, phosphorus is increased, and nitrate nitrogen is very low. The content of humus is high compared with regional sod–podzolic soils (Table 1).

Udmurtskaya street is one of the largest and busiest city thoroughfares. Studied plants were located in the area along the pipeline, having a length of more than 2 km, between the streets Mayskaya and Votkinskoe shosse. The plot was characterized by heavy vehicular traffic (2800 cars h^{-1}). The content of organic matter (humus) in the soil of roadside hedgerows was 2.3%. The main elements of mineral nutrition were characterized by a high content, except for very low concentrations of nitrate nitrogen—5.13 mg kg^{-1} of soil. The acidity of the soil solution was slightly alkaline and alkaline (Table 1).

RESULTS AND DISCUSSION

The vital condition indicators of barbed spruce in the Kirov Park were as follows: healthy individuals

Table 2. Morphometric parameters of the annual vegetative shoot of conifers (2011–2012)

Species	Year	The area of the needles, mm^2	The mass of the needles in air-dried condition, g	Shoot lenght, cm	Number of needles on the annual shoot, pcs.
Kirov Park					
Norway spruce	2011	27.96 ± 0.58	0.36 ± 0.02	4.63 ± 0.19	64.33 ± 4.33
		25.48...30.44	0.26...0.47	3.84...5.43	45.69...82.98
	2012	25.38 ± 2.43	0.41 ± 0.03	6.47 ± 0.29	77.00 ± 8.50
		14.91...35.84	0.28...0.54	521...7.72	40.41...113.59
Barbed spruce	2011	58.37 ± 1.06	0.73 ± 0.11	5.97 ± 0.99	103.67 ± 15.43
		53.83...62.92	0.25...1.21	1.69...10.24	37.27...170.06
	2012	56.13 ± 2.72	0.95 ± 0.01	6.13 ± 1.49	85 ± 17.93
		44.43...67.84	0.88...1.01	–0.27...12.54	7.87...162.13
ul. Udmurtskaya					
Norway spruce	2011	29.77 ± 4.35	0.29 ± 0.08	4.63 ± 0.32	65.67 ± 7.13
		11.05...48.49	–0.06...0.63	3.27...6.00	35.00...96.33
	2012	26.76 ± 3.92	0.38 ± 0.11	4.70 ± 0.36	66.33 ± 5.90
		9.88...43.64	–0.09...0.84	3.15...6.25	40.96...91.71
Barbed spruce	2011	106.71 ± 11.79	2.67 ± 0.99	6.13 ± 0.93	114.33 ± 15.65
		55.98...157.43	–1.59...6.92	2.15...10.12	47.02...181.65
	2012	86.24 ± 10.26	2.49 ± 0.44	4.53 ± 0.22	74.33 ± 4.81
		42.10...130.38	0.59...4.39	3.59...5.47	53.65...95.02
RC Sever					
Norway spruce	2011	25.03 ± 1.12	0.40 ± 0.05	9.13 ± 0.86	101.00 ± 4.00
		20.21...29.85	0.18...0.61	6.99...11.27	83.79...118.21
	2012	32.57 ± 4.79	0.45 ± 0.02	7.17 ± 0.71	138.33 ± 15.24
		11.95...53.18	0.38...0.51	5.40...8.93	72.78...203.89
Barbed spruce	2011	96.98 ± 7.57	1.44 ± 0.15	7.07 ± 1.01	105.33 ± 5.93
		64.42...129.53	0.79...2.10	4.55...9.58	79.84...130.83
	2012	70.38 ± 17.69	0.98 ± 0.13	8.90 ± 0.75	127.33 ± 11.33
		5.72...146.49	0.40...1.55	7.02...10.77	78.57...176.10

made up 37.0%, weakened were 31.5%, and severely weakened were 31.5%. Fifty percent of individuals of Norway spruce in the park plantings had a weakened vital state, 30% were in a healthy state, and 20% were severely weakened (deadwood). Diseases and pests were not found on the studied trees, and the decreased vital condition was associated with the presence of stem defects.

Conifer plantings in residential areas were represented mainly by the trees of a healthy vital state: barbed spruce, 100%, and Norway spruce, 82%.

Our studies of the vital condition of conifers in roadside hedgerows showed that 50% of spruce individuals were in a weakened state and 50% were healthy. The reduced vital state of spruce was related to the presence of stem and crown defects, as well as the damage of the plantings by bark beetle (through holes were found), but no dead trees were found.

The vital state of barbed spruce plantations in roadside hedgerows was as follows: 33.3% for each of healthy, greatly weakened, and severely weakened individuals. The main defects of the trees were one-sided crown, split trunk, dry branches in the crown, frost cracks, mechanical damage, pitching, and sprout. It should be noted that the above trunk defects were found in all studied areas.

The relative vital state of the trees was generally weakened and accounted for 70–76%.

The features of plant growth were evaluated by morphometric parameters of the annual increment of the shoots (Table 2).

The maximum length of the shoots of Norway spruce was observed in residential areas (RC Sever), where the indicators were significantly higher than in the park. Some authors indicate a decrease in the size of the shoots (xerophytization) of deciduous tree species in a man-made environment (Neverova and Kolmogorova, 2003). There were no significant changes in the length of the shoots of barbed spruce; the needles had a strong cuticular layer, which made this species more resistant to air pollution by industrial gases.

Norway spruce in the plantings of RC Sever had a significant increase in the number of needles in the annual shoots compared with a park with no significant differences in other morphometric parameters. Barbed spruce from the plantings of RC Sever had an increased area of needles compared with the control plot, while other morphological indicators of annual growth were not significantly different from control. There were no significant differences in the morphological indicators of the annual increment for studied years, either.

The ability of a plant organism to perform photosynthetic activity is one of the most important indicators of plant activity under stress and their environment-regulating role. The content of pigments and their relationship is a very important indicator, determining the adaptive properties of plants.

The principal components method was used to identify the studied plant parameters, which vary depending on the environmental load. As a result, we identified the two principal components in all types of plantings (Table 3). Analyzing the dual variability of traits in the studied tree species, we were able to establish that the first principal component reflects the parameters of the content of chlorophyll A and carotenoids in the plant assimilation apparatus in the plantings of the Kirov Park (conditional control zone). In barbed spruce, it had a highly significant negative correlation with the content of chlorophyll A (correlation coefficients –0.88 to –0.98) and carotenoids (–0.93 to –0.99), while Norway spruce positively correlated with their content (respectively, 0.99 to 0.97 and 0.99 to 0.95). This component accounted for 77% of the variability. Principal component 2 covered 23% of the variability; it had a highly significant negative correlation with chlorophyll content in the needles of Norway spruce (–0.78 to –0.96) and a positive correlation with the content of the same pigment in the needles of barbed spruce (0.33 to 0.73).

The first principal component reflected the parameters of the content of all analyzed pigments in the needles of Norway spruce (2012) and barbed spruce (2013) in the plantings of RC Sever. It had a highly significant negative correlation with these indicators, accounting for 62% of the variability. Principal component 2 covered 38% of the variability; it had a highly significant positive correlation with the content of the pigments in the needles of barbed spruce in 2012.

In roadside hedgerows, the first principal component (accounting for 59% of the variance) reflected the parameters of the content of chlorophylls *a*, *b*, and carotenoids in the needles of both studied plant species, established in 2013, and had a highly significant positive correlation with these parameters. Principal component 2 covered 41% of the variability; it had a highly significant negative correlation with the content of the pigments in the needles of barbed spruce (2012).

Plotting the position of the objects in the coordinate axes of the principal components 1 and 2 showed that the indices of the content of chlorophyll A and carotenoids in Norway spruce growing in the plantings of Kirov Park (Fig. 1a) combined into one group and to another group in barbed spruce. At the same time, the content of chlorophyll B significantly correlated with the principal components. In the residential area, no clear patterns of association of indicators in the groups were observed (Fig. 1b). The association of all indicators in the groups on the basis of species was observed under conditions of more intensive anthropogenic impact (Fig. 1c).

Multivariate analysis of variance was performed to determine the effect of specific features, conditions in the place of growth, and the impact of these factors on the content of photosynthetic pigments performed; it showed the significance of the impact of these factors and their influence (at $p < 0.5$) on the studied parameters. Our findings are consistent with recent results (Bukharina et al., 2014; Vedernikov et al., 2014).

Studying the dynamics of chlorophyll *a* in the needles of barbed spruce, it was found that its content during the growing season changed significantly only in the plantings of RC Sever; it increased in August compared to July and then decreased sharply in October. This pattern was identified in both studied years (Table 4).

Comparing the content of chlorophyll *a* in the needles of barbed spruce in different types of plantings during two growing seasons, we found that significant differences were observed in the plantings of RC Sever when compared with those in the CCZ: in August 2012 and 2013, the content of chlorophylls was higher on 0.67 and 0.73 mg g^{-1} of dried matter, respectively; in the roadside hedgerows, in October it was higher on 0.30 and 0.31 mg g^{-1} of dried matter than in CCZ (at $LSD_{0.5} = 0.15$ in 2012 and $LSD_{0.5} = 0.30$ in 2013).

The dynamics of chlorophyll *a* in the needles of Norway spruce showed that its content changed significantly during the observation period only in the park plantings (CCZ) in 2012. In August the indicator decreased to 0.52 mg g^{-1} of dried matter compared with July (0.76 mg g^{-1} of dried matter; in October it increased to 1.15 mg g^{-1} of dried matter. Thus, it was found that the dynamics of chlorophyll A content in the studied species of spruce is different in the plantings of the city. However, the content of chlorophyll *a* in Norway spruce was significantly lower than that in

Table 3. Correlation coefficients of initial traits with the principal components

Species/indicator/year	Studied plots					
	Kirov Park		RC Sever		ul. Udmurtskaya	
	principal component 1	principal component 2	principal component 1	principal component 2	principal component 1	principal component 2
Barbed spruce chlorophyll *a*, 2012	−0.883	−0.467	−0.270	0.963	0.653	−0.759
Barbed spruce chlorophyll *b*, 2012	−0.945	0.326	0.014	0.999	−0.015	−0.999
Barbed spruce carotenoids 2012	−0.931	−0.364	−0.410	0.912	0.423	−0.906
Norway spruce chlorophyll *a*, 2012	0.994	0.102	−0.973	0.232	−0.219	−0.976
Norway spruce chlorophyll *b*, 2012	0.623	−0.781	−0.999	−0.051	−0.767	−0.642
Norway spruce carotenoids, 2012	0.999	−0.004	−0.826	0.563	−0.492	−0.870
Barbed spruce chlorophyll *a*, 2013	−0.984	0.173	−0.989	−0.144	−0.987	−0.161
Barbed spruce chlorophyll *b*, 2013	−0.680	0.733	−0.999	−0.013	−0.972	0.235
Barbed spruce carotenoids-2013	−0.985	0.172	0.989	−0.148	−0.994	0.108
Norway spruce chlorophyll *a*, 2013	0.968	0.249	−0.657	−0.754	−0.937	−0.349
Norway spruce chlorophyll *b*, 2013	−0.267	−0.964	−0.950	−0.312	−0.884	0.468
Norway spruce carotenoids 2013	0.954	0.298	−0.552	−0.834	−0.999	0.009
Absolute values of variability	9.243	2.757	7.464	4.536	7.049	4.951
Proportion of the variability attributable to the principal component	0.770	0.229	0.622	0.378	0.587	0.413

Conventions are applicable to Figs. 1a, 1b, and 1c.

barbed spruce in all plantings for both years of research. On this basis, we can assume that the stability and the high content of chlorophyll *a* is one of the reasons for the resilience of barbed spruce in urban conditions.

A comparison of different types of plantings revealed that the content of chlorophyll *a* in the plants of Norway spruce from roadside hedgerows was significantly lower when compared to the park plantings at the end of the growing season (October) for both years of observations (at 0.37–0.4 mg g^{-1} of dried matter).

It should be noted that the content of chlorophyll *b* in Norway spruce increased with reducing content of chlorophyll *a* (e.g., in park plantings in August 2012), and, on the contrary, it decreased with increasing content of chlorophyll *a*.

Studying the dynamics of chlorophyll *b* in barbed spruce showed that there was no significant changes in the content of the pigment during the growing season and in different types of plants in both studied years. In Norway spruce, the content of chlorophyll *b* during the growing season changed significantly in the plantings of the CCZ and roadside hedgerows. The highest chlorophyll content indicators were marked in August.

Comparing the content of chlorophyll *b* in the studied species from different types of plantings at the end of the growing season, a significantly lower content of the pigment was noted for the plants from the plantings in RC Sever when compared with the CCZ.

Studying the dynamics of the content of carotenoids in the needles of barbed spruce revealed a significant increase in the carotenoids in the roadside hedgerows in October, that is, at the end of the active growing season, when compared to July. In Norway spruce, an increase in the content of carotenoids occured in all types of plantings in October compared to July, which was certainly evidence for the protective antioxidant role of the pigment. A comparison of different types of plantings showed that the content of carotenoids in barbed spruce was higher than in the CCZ in a residential area in August. The content of the pigment in the roadside hedgerows of Norway spruce (October) and the plantings of the residential area (August) was, on the contrary, significantly lower than in the park plantings.

The cytological study of spruce needles from the industrial zone revealed the accumulation of phenolic compounds in its tissues. In recent years, the possible role of phenolic compounds (including tannins) as a protection of viable tissues and their involvement in the aging process has been discussed (Fuksman et al., 2005), and the role of tannins as antioxidants was also noted.

At this stage, the analysis of the content of tannins in the roots of the studied plants was performed (Table 5). The root system, directly contacting with urbanozem, performs the barrier function, controlling (preventing) the penetration of pollutants into the plant. However,

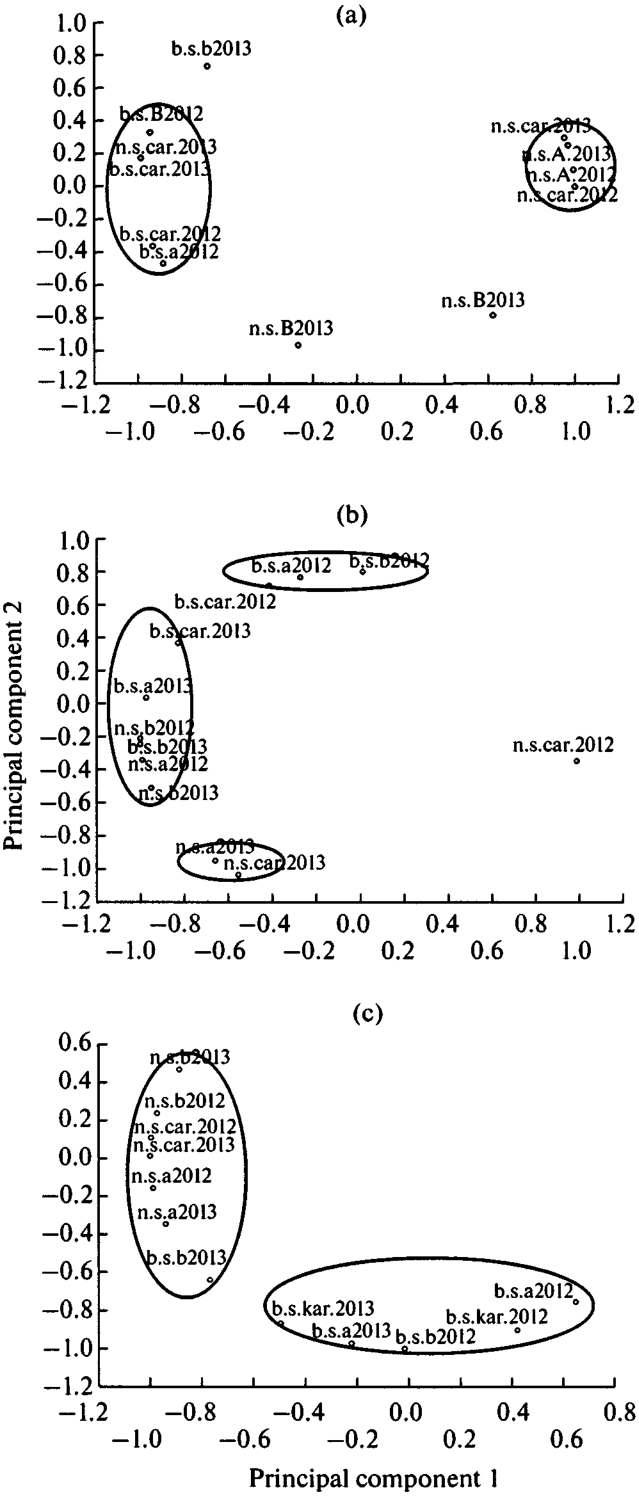

Fig. 1. Distribution of the indicators of the content of the pigments in the needles of barbed spruce and Norway spruce on the plane in the coordinates of the principal components 1 and 2; (a) Kirov Park, (b) RC Sever, (c) ul. Udmurtskaya; b.s.—barbed spruce, n.s.—Norway spruce, a—chlorophyll *a*, b—chlorophyll *b*, and car.—carotenoids.

Table 4. Content of photosynthetic pigments in the needles of barbed spruce and Norway spruce in the plantings of Izhevsk, 2012–2013

Species	Studied plot	Year	Photosynthetic pigments, mg g^{-1} of dried matter								
			chlorophyll *a*			chlorophyll *b*			carotenoids		
			July	August	October	July	August	October	July	August	October
Barbed spruce	Kirov Park	2012	0.75	0.66	0.72	0.16	0.21	0.12	0.28	0.23	0.38
	ul. Udmurtskaya		0.88	0.80	1.02*	0.16	0.22	0.18	0.32	0.34	0.51**
	RC Sever		1.01*	1.33*, **	0.52*,**	0.32	0.29	0.12	0.34	0.37	0.28
	Kirov Park	2013	0.62	0.53	0.62	0.12	0.18	0.11	0.22	0.19	0.33
	ul. Udmurtskaya		0.72	0.79	0.92*	0.12	0.21	0.14	0.26	0.31	0.46**
	RC Sever		0.93*	1.26*, **	0.45**	0.31	0.36	0.61	0.29	0.49*, **	0.24
Norway spruce	Kirov Park	2012	0.76	0.42**	1.15**	0.14	0.53**	0.19	0.29	0.38	0.61**
	ul. Udmurtskaya		0.81	0.71	0.78*	0.15	0.45**	0.10	0.32	0.26	0.45*
	RC Sever		0.78	0.44**	0.85*	0.47*	0.21*	0.35	0.22	0.13*	0.58**
	Kirov Park	2013	0.64	0.71	1.11	0.19	0.41	0.17	0.29	0.29	0.59**
	ul. Udmurtskaya		0.81	0.79	0.71*	0.14	0.23	0.73*, **	0.24	0.32	0.41*, **
	RC Sever		0.58	0.42	0.81*	0.20	0.28	0.74*, **	0.20	0.13	0.48**
LSD$_{0.5}$		2012	0.15			0.32			0.15		
		2013	0.30			0.50			0.14		

* Significant differences in the plantings compared with conventional control zone ($p < 0.5$).
** Significant differences in August and October compared with July ($p < 0.5$).

cell properties, namely, protoplast permeability, are violated upon a high anthropogenic load, which leads to the saturation of roots with heavy metals. In turn, tannins, which perform the role of antioxidants, are accumulated in the roots to neutralize the contaminants.

The analysis revealed that the content of tannins in the roots of Norway spruce from the park plantings (CCZ) exceeded that of barbed spruce. The content of tannins in the roots of Norway spruce from the city plantings was significantly reduced almost twice. The content of tannins in barbed spruce from the roadside hedgerows was almost twice as high as in the plantings of the CCZ; the differences were not significant in the plantings of RC Sever.

Table 5. Content of tannins in the roots of conifers, mg 100 g^{-1} of dried matter

Studied plot	Barbed spruce	Norway spruce
Kirov Park	2.3 ± 0.1	7.2 ± 0.4
	1.9...2.6	6.3...8.0
ul. Udmurtskaya	4.0 ± 0.0	3.2 ± 0.3
	4.0...4.0	2.4...3.9
RC Sever	1.8 ± 0.2	3.5 ± 0.0
	1.4...2.3	3.4...3.5

The top line in Table 5 is the average value of the indicator ± standard deviation; the bottom line is the confidence interval for the mean value.

CONCLUSIONS

This research made it possible to evaluate the state of the two species of coniferous arboreous plants and their plantings, to identify the features of their response to the growing conditions, to perform a comparative analysis of the studied species for a set of morphological and physiological characteristics, and to determine their resilience to the high level of pollution in the urban environment.

There were no significant differences in the biomorphology of the annual increment in Norway spruce and barbed spruce in the years of research. High indicators of the number of needles on the annual shoot and the length of the annual shoot were marked for the plantings of Norway spruce in the residential area, but there were no significant differences from the conditional control zone in the parameters of area and mass of the needles. A significant increase in the area of the needles on the annual shoot was found in barbed spruce in the plantings of the residential area.

Processing the results of the principal component analysis on the content of photosynthetic pigments in the needles of plants showed that the layout of studied objects in the coordinate axes of the principal components in both roadside hedgerows and a residential area differed from the conditional control zone. The differences were caused by a different correlation with the principal components of the content of photosynthetic pigments and the growing season in the studied plant species.

The relative stability of the content of chlorophyll *a* and *b*, as well as higher concentrations of chlorophyll *a* compared to Norway spruce, were observed in the urban plantings of barbed spruce.

The content of carotenoids in the needles of plants from different types of plantings showed that there was almost a double increase in its content in the plantings of RC Sever (August 2012), whereas it decreased by 0.22 mg g^{-1} of dried matter in the plantings of in Norway spruce from RC Sever (at LSD = 0.5) and by 0.18 mg g^{-1} of dried matter in the roadside hedgerows (October 2013) (at LSD = 0.5).

In general, it should be noted that the values of the indicators of the content of photosynthetic pigments in barbed spruce and Norway spruce were significantly higher in 2012 compared to 2013 due to differences in weather conditions.

The changes in the content of tannins in the plant root system of the studied species were different because of the growing conditions. In Norway spruce, an almost two-fold significant reduction in the content of tannins was found in the plantings of the residential areas and roadside hedgerows upon their higher content in the plants from the park zone. The content of tannins in barbed spruce had either no differences from control (plantings in the residential area) or was significantly higher (roadside hedgerows) than in the park zone.

The results indicate pronounced adaptive capabilities of the photosynthetic apparatus of barbed spruce, which serves as a basis to recommend this species for wider use in the plantings of the city.

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REFERENCES

Alekseev, V.A., Diagnostics and classification of forest ecosystems damaged by pollution, in *Lesnye ekosistemy i atmosfernoe zagryaznenie* (Forest Ecosystems and Atmospheric Pollution), Leningrad: Nauka, 1990, pp. 38–53.

Bukharina, I.L. and Povarnitsina, T.M., Ecological and biological characteristic of *Picea pungens* (Pinaceae) in urban conditions, *Rastit. Resur.*, 2013, vol. 49, no. 3, pp. 312–318.

Bukharina, I.L., Povarnitsina, T.M., and Vedernikov, K.E., *Ekologo-biologicheskie osobennosti drevesnykh rastenii v urbanizirovannoi srede* (Ecological and Biological Features of Wood Plants in Urban Environment), Izhevsk: Izhevsk. Gos. S-kh. Akad., 2007.

Bukharina I.L., Vedernikov K.E., Kamasheva A.A., Alekseenko A.S., and Pashkov E.V. Ecological and biological features of Colorado spruce (*Picea pungens* Engelm.) in urban environment, *Adv. Environ. Biol.*, 2014, no. 8 (13), pp. 367–371.

Bukharina, I.L., Zhuravleva, A.N., and Bolyshova, O.G., *Gorodskie nasazhdeniya: ekologicheskii aspekt* (Urban Plantations: Ecological Aspect), Izhevsk: Udmurt. Gos. Univ., 2012.

Chernyshenko, O.V., Dust-filtering ability of wood plants in a city and its ecological significance, in *Ekologiya, monitoring i ratsional'noe prirodopol'zovanie* (Ecology, Monitoring, and Rational Nature Managements), Moscow: Mosk. Gos. Univ. Lesa, 2001, no. 307 (1).

Fuksman, I.L., Novitskaya, L.L., Isidorov, V.A., and Roshchin, V.I., Phenolic compounds of coniferous trees in stress conditions, *Lesovedenie*, 2005, no. 3, pp. 4–10.

Gavrilenko, V.F. and Zhigalova, T.V., *Bol'shoi praktikum po fotosintezu* (Large Practical Manual on Photosynthesis), Moscow: Academia, 2003, pp. 42–58.

GOST (State Standard) *2140-81: Visible Defects of Wood. Classification, Terms, and Definitions, Methods of Measurement*, Moscow: Izd. Standartov, 1982.

GOST (State Standard) *17.54.01-84: Nature Protection. Land Reclamation. General Requirements for Lands to be Backfilled*, Moscow: Izd. Standartov, 1984.

GOST (State Standard) *26483-85: Soils. Preparation of Salt Extract and Determination of its pH by CINAO Method*, Moscow: Izd. Standartov, 1987.

Il'minskikh, N.G., Location of Izhevsk city on geographical map, in *Priroda Izhevska i ego okrestnostei* (Nature of Izhevsk City and Its Vicinities), Izhevsk: Udmurtiya, 1998, pp. 7–9.

Ivanov, L.A., Morphological and biochemical features of the plants in boreal zone with different types of adaptive strategies, *Extended Abstract of Cand. Sci. (Biol.) Dissertation*, Tomsk: Tomsk State Univ., 2001.

Karasev, V.N., *Fiziologiya rastenii: uchebnoe posobie* (The Plant Physiology: Manual), Yoshkar-Ola: Mariisk. Gos. Tekh. Univ., 2001.

Karpuk, V.V., *Farmakognoziya: uchebnoe posobie* (Pharmacognosy: Manual), Minsk: Beloruss. Gos. Univ., 2011.

Koval'chuk, A.G., Ermakova, T.N., and Ryzbov, D.S., *Doklad ob ekologicheskoi obastanovke v g. Izhevske v 2013 g.* (A Report on Environmental Situation in Izhevsk City in 2013), Izhevsk, 2014.

Koval'skii, V.V., *Geokhimicheskaya ekologiya (Geochemical Ecology)*, Moscow: Nauka, 1974.

Krasnoshchekova, N.S., *Ekologo-ekonomicheskaya effektivnost' zelenykh nasazhdenii: obzornaya informatsiya* (Ecological-Economic Efficiency of Green Plantations: Review), Moscow: Minzhilkomkhoz RSFSR, 1987.

Kretovich, V.L., *Ocnovy biokhimii rastenii* (Fundamentals of the Plant Biochemistry), Moscow: Vysshaya Shkola, 1986.

Kulagin, A.A. and Shagieva, Yu.A., *Drevesnye rasteniya i biologicheskaya konservatsiya promyshlennykh zgryaznitelei* (Wood Plants and Biological Conservation of Industrial Pollutants), Moscow: Nauka, 2005.

Kurbatova, A.S., Bashkin, V.N., and Kasimov, N.S., *Ekologiya goroda* (Urban Ecology), Moscow: Nauchnyi Mir, 2004.

Kuznetsov, M.F., *Khimicheskii analiz pochv i rastenii v ekologicheskikh issledovaniyakh: uchebnoe posobie* (Chemical Analysis of the Soils and Plants in Ecological Studies: Manual), Izhevsk: Udmurt. Gos. Univ., 1994.

Neverova, O.A. and Kolmogorova, E.Yu., *Drevesnye rasteniya i urbanizirovannaya sreda* (Wood Plants and Urban Environment), Novosibirsk: Nauka, 2003.

Sokolov, P.A., *Taksatsiya lesa. Tom 1. Taksatsiya otdel'nykh derev'ev* (Forest Inventory, Vol. 1: Inventory of Single Trees), Yoshkar-Ola: Mariisk. Gos. Tekh. Univ., 1998.

Troshkova, I.Yu. and Vinokurova, R.I., Accumulation of betulin and suberin in *Betula pendula* bark growing on the territories for various purpose, *Mater. Vseros. nauchno-prakt. konf. "Sovremennye problemy agrarnoi nauki i puti ikh resheniya"* (Proc. All-Russ. Sci.-Pract. Conf. "Modern Problems of Agrarian Science and Their Solutions"), Izhevsk: Izhevsk. Gos. S-kh. Akad., 2005, pp. 278–282.

Vedernikov K., Bukharina I., and Alekseenko A. Environmental assessment and the use of plants of the genus *Picea* forests of the city of Izhevsk, *Austral. J. Sci. Res.*, 2014, vol. 3, no. 1 (5), pp. 243–248.

Veretennikov, A.V., *Fotosintez drevesnykh rastenii* (Photosynthesis of Wood Plants), Voronezh: Voronezh. Gos. Univ., 1980.

Voskresenskaya, O.L., *Ekologo-fiziologicheskie adaptatsii tui zapadnoi (Thuja occidentalis L.) v gorodskikh usloviyakh* (Ecological and Physiological Adaptations of Eastern White Cedar *Thuja occidentalis* L. in Urban Environment), Yoshkar-Ola: Mariisk. Gos. Univ., 2006.

Yagodin, B.A., Deryugin, I.P., Zhukov, Yu.P., Demin, V.A., Peterburgskii, A.V., Kidin, V.V., Slipchik, A.F., Kulyukin, A.I., and Sablina, S.M., *Praktikum po agrokhimii* (Practical Manual on Agricultural Chemistry), Moscow: Agropromizdat, 1987.

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