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Relationship between the Characteristics of the State of Scots Pine Trees and Tree Stands in a Large Industrial City

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Abstract—The characteristics of the state of individual pine trees and tree stands are analyzed in areas with different levels of urbanization, which are within the urban zone of the city of Yekaterinburg, city parks, and forests outside the city. In the city parks, the state of tree stands does not differ much from the state of forests growing outside the city, but inside the city the timber stock is observed to decrease. Statistical analysis showed this effect to be due to summation of changes in stand density and trees size, and the worsened sanitary tree status, which is reliably due to environmental pollution and recreation, accounts only for a small part of the changes in the timber stock. Mature tree stands are shown to stay resistant to negative environmental impacts for a long time.

Keywords: Scots pine, city tree stands, urban forestry, tree vitality, productivity

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Knowing the specificity of forest use under urban conditions has led to the formation of a separate field of forest science: urban forestry, which is at the interface of science, art, and technology for management of natural forests and artificial tree stands in urban areas (Konijnendijk et al., 2006; McPherson, 2006; Rysin, L.P. and Rysin, S.L., 2007, 2011). The tasks of studying and managing city tree stands are interrelated, since the cognition of the viability mechanisms in trees and tree stands is necessary to develop actions for stabilizing their ecological and social functions under urban conditions (Rysin, L.P. and Rysin, S.L., 2007, 2011). On the whole, the results of studying urbanized forests indicate the regular weakening of individual trees, worsening of their vital and sanitary status, significant liability to phytopathogenic invasions, and total decrease in the resistance of city tree stands up to their complete destruction. This is caused by different factors and can be due to the impact of different mechanisms: the physiological mechanism, for example, direct damage by pollutants (Il'kun, 1978; Kulagin, 1985; Onuchin and Kozlova, 1993; Chernen'kova, 2002; Shergina and Mikhailova, 2007); the ontogenetic mechanism, which is due to pessimal conditions and worsened resource stock (Kulagin, 1985; Vedernikov and Bukharina, 2010); the population mechanism, for example, the transformation of the age structure and decrease in the success of renewal (Repshas, 1994; *Ekologicheskoe*…, 2009; Tolkach, 2011; Tolkach and Dobrotvorskaya, 2011), and the ecological mechanism, for example, root nutrition, and phytopathogenic invasions (Lebedev, 1998; Koltunov et al., 2007; Shergina and Mikhailova, 2007; Selochnik, 2008; Veselkin and Kaigorodova, 2013; Veselkin et al., 2013).

It is important to ascertain how individual indicators of the state of individual trees, for example, their growth and sanitary characteristics, are interrelated with the general status and environment-stabilizing functions of city tree stands. There are two aspects of analyzing this interrelation: first, how much the transformation of different signs of the vital status in individual trees affects the integral characteristics of a tree stand; second, what easily, precisely, or ordinarily measured indicators of the status of individual trees are expedient to be used as indicators of the tree-stand status for the purpose of optimizing monitoring studies.

The goal of the work was to assess how much the parameters of the tree status and forestry-taxation characteristics of pine forest stands are transformed in a large industrial city (using the city of Yekaterinburg as an example) in order to ascertain which signs of the organism level are most closely interrelated with the parameters that determine the environment-stabilizing functions of city tree stands. We believed the timber stock to be the key characteristic, which is related to the performance of such functions (the participation in the turnover of biogenic elements, regulation of the gas composition and microclimate, and the deposition of pollutants). In other words, our task was to

Table 1. Visitability and recreational damage of suburban and urbanized areas

Characteristics	Areas		
	suburban areas	parks	city areas
Population in a radius of 1 km from *TPs* with the use of different predictors (median and range):			
preschools, thousand people	0	7 (0–37)	24 (3–57)
drugstores, thousand people	0	3 (0–24)	24 (3–51)
Degree of recreational digression, score (median and range)	2 (0–4)	2 (0–4)	4 (2–5)

reveal the parameters of the tree status, which are most closely interrelated with the change in the total productivity of tree stands.

MATERIALS AND METHODS

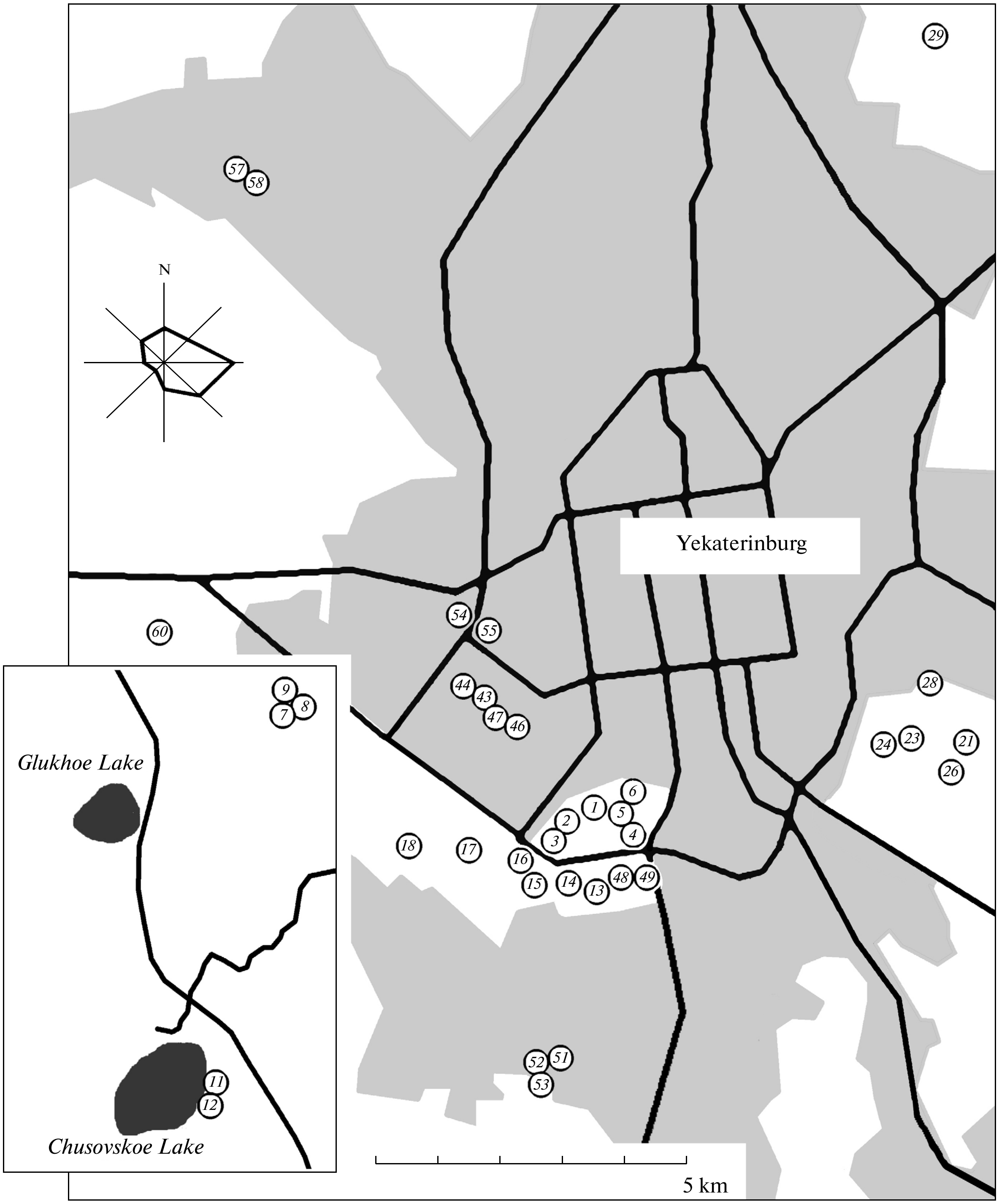
Studied Region

Yekaterinburg is an industrial megalopolis of the Middle Urals with an area of 49 800 ha and population of about 1.4 million citizens and one of the largest Russian cities. According to the forest growth zoning of B.P. Kolesnikov (1973), it is in the southern taiga district of the Trans-Ural hilly submountain province. Pine forests on sod–podzol soils and brown soils are prevalent in the territories around Yekaterinburg. Owing to the significant number of industrial enterprises, the territory of Yekaterinburg is strongly polluted (Sturman, 2008). In 2010–2012, atmospheric emissions were about 190 000–215 000 t/year (sulfur, carbon, and nitrogen compounds, as well as mineral dust, and heavy metals), of which nitrogen compounds accounted for about 10 000–12 000 t. The soils of Yekaterinburg are polluted with heavy metals: according to the data of 2010, the maximum content of copper, nickel, lead, chrome, zinc, cadmium, and manganese in the soils of the city center surpassed the background values by factors of 58, 20, 18, 8, 6, and 3, respectively (*Gosudarstvennyi doklad*…, 2011). The greatest contribution to atmospheric pollution (up to 85%) is made by urban motor transport (Sturman, 2008; *Gosudarstvennyi doklad*…, 2011, 2013). Almost a third (15300 ha) of the territory of Yekaterinburg is occupied by city parks and city tree stands, most of which are of natural origin. City parks are for the most part concentrated in the urban periphery; most of them neighbor the adjacent forests outside the city or agricultural areas.

Test Plots

The studies are based on the materials obtained in 2012 in permanent and temporary test plots (*TPs*), which are situated in the territory of the city of Yekaterinburg and its nearest environs (figure). The test plots were placed in the city in the areas with a different density of residential buildings: in city parks (Southwestern, Lesovodov Rossii, Kalinovskii, and Sem' Klyuchei parks and the arboretum of the Botanical Garden of the Ural Branch, Russian Academy of Sciences (UB RAS)) and in pine stands and sites within the residential area (city tree stands isolated from the main city park ring in the 1970s–1980s, i.e., 40–30 years ago).

Consequently, tree stands of three variants are compared: suburban tree stands ($n = 6$), city parks ($n = 20$), and city tree stands ($n = 11$) (in total, 37 *TPs*). These three categories of tree stands are arranged into gradient according to the degree of transformation of areas, which is designated as an urbanization gradient. In this case, urbanization is understood widely: all direct and indirect impacts of urban building on natural ecosystems. The estimates of population in a radius of 1 km from the *TPs* (obtained using DubleGIS-Yekaterinburg software with an assumption that one preschool corresponds to 3300 people and one drugstore accounts for 2700 people) and the estimated degrees of the recreational digression of the aboveground cover in the *TPs* were used as characteristics of the recreational impact according to OST 56-100-95 (Table 1). The clear distinctions in visitability and the degree of recreational damage are evident both between the suburban tree stands and city parks and between the city parks and park fragments in the residential area. The estimates of the atmospheric concentration of NO_2, which is almost exclusively contained in motor transport emissions (Antropov and Varaksin, 2011), were used in order to characterize the degree of environmental pollution. Suburban *TPs* (nos. 7–9, 11, 12, and 60) are all characterized by the minimum range of average daily NO_2 concentrations (0–9 μg/m^3). In the city parks in seven *TPs* (nos. 17, 18, 21, 23, 24, 26, and 29), NO_2 is present in a concentration of 0–9 μg/m^3; in eleven *TPs* (nos. 1–3, 5, 6, 13–16, 28, and 58) its concentration is 10–19 μg/m^3; and in two *TPs* (nos. 4 and 57) its concentration is 20–50 μg/m^3. In the residential area, three *TPs* (nos. 51–53) are characterized by the minimum (0–9 μg/m^3) concentrations of NO_2, four *TPs* (nos. 43 and 46–48) have intermediate concentrations (10–19 μg/m^3), and four *TPs* (nos. 44, 49, 55, and 54) have the maximum concentrations (20–50 μg/m^3).



Layout of test plots (marked with circles; ciphers are numbers of *TPs*) in the residential area of Yekaterinburg (the gray background; lines are main transport roads) in city parks and suburbs. The suburban area in the environs of the Glukhoe and Chusovskoe lakes is 8–10 km to the west of the boundary of the residential area.

MATERIALS AND METHODS

The criteria for selection of the *TPs* were as follows: (1) the origin of tree stands is natural, (2) the share of the pine in the timber stock is more than 90%, (3) the average tree age in the major tier is no less than 110 years, (4) the tree stands are placed in transit relief elements (i.e., they are not in gullies and depression bottoms but also are not in eluvial positions), and the forest growth conditions in all plots correspond to the motley-grass group of forest types. The absence of fresh and/or purposeful anthropogenic damages of soil cover (roads and upturned areas), tree stands (fires and

Table 2. Characteristics of pine forest stands in suburban and urbanized stands ($m \pm$ SE)

Characteristics	Areas			Significance of differences			
	suburban areas ($n = 6$)	parks ($n = 20$)	city areas ($n = 11$)	ANOVA		ANCOVA	
				F or H	P	F	P
Tree characteristics							
Diameter, cm (D)	41 ± 2	42 ± 1	37 ± 2	1.54	0.228	0.35	0.709
Height, m (H)	27 ± 1	27 ± 1	25 ± 1	3.05	0.061	1.67	0.216
Age, years (A)	127 ± 7	130 ± 3	115 ± 4	3.58	0.039	–	–
Damage index, score (I)	2.5 ± 0.1	2.9 ± 0.1	3.1 ± 0.1	5.75	0.007	5.04	0.012
Degree of defoliation, % (F)	38 ± 4	41 ± 1	47 ± 2	4.03	0.027	2.88	0.070
Needle lifespan, years (L)	2.3 ± 0.1	2.1 ± 0.1	1.9 ± 0.1	6.57	0.004	5.14	0.011
Characteristics of forest stands							
Forest stand density, sp./ha	331 ± 42	311 ± 31	318 ± 54	0.04	0.961	0.35	0.710
Growth class, score (B)	II	I–IV	I–IV	2.62	0.270	–	–
Stock of living wood, m^3/ha (M)	466 ± 34	452 ± 18	348 ± 30	5.87	0.006	7.13	0.003
Share of dead wood in timber stock, % (T)	1.2 ± 0.8	1.9 ± 0.4	0.9 ± 0.6	1.06	0.358	0.33	0.723

n is the number of test plots; ANOVA is the single-factor dispersion analysis ($dF_{factor} = 2$; $dF_{error} = 34$); ANCOVA is the single-factor covariation analysis ($dF_{factor} = 2$; $dF_{error} = 33$; a covariant is the middle tree age in a test plot); F is the Fisher criterion; H is the Kruskel-Wallis criterion (it was calculated only for the growth class); P is the achieved level of significance; the gap means that the estimation is impossible.

felling), and living aboveground cover (mowing) are additional criterion for selection.

The test plots in the suburban areas and city parks were laid according to OST 56-69-83 with an area of 0.3 ha (50 × 60 m) with the number of trees in the major tier of 70–190 sp. per *TP*. In urban areas, the studies were performed in the accounted forest plots with an area of 0.0625 ha (25 × 25 m) with the number of trees of 10–40 sp. (Anuchin and Yaroslavtsev, 2004). Trees were totally counted in each *TP* while measuring trunk diameter at a height of 1.3 m by a caliper with an accuracy of up to 1 cm and estimating height by an electronic altimeter with an accuracy of 0.5 m. Age was determined based on core samples, which were taken by an age drill in 6–10 model samples in each *TP* and selected in proportion to the representation of trees with different degrees of thickness. The vital tree status was assessed visually by the standard methods: the damage class was determined for each tree on a 6-point scale (Alekseev, 1997; *OST*..., 1995), obtaining the tree damage index per *TP* by averaging the damage values. The degree of crown defoliation (*Sanitarnye pravila*…, 1998) and average needle lifespan (*Manual*…, 1994) were also determined for each tree.

A *statistical analysis* was performed in the STATISTICA v. 6.0 package. The use of parametric methods (the ANOVA and ANCOVA, regression and correlation analysis) is grounded by the satisfactory results from checking the normality of variable distribution in advance and estimating homogeneity of variance according to the Levene criterion. The nonparametric variants of the ANOVA (the Kruskal–Wallis criterion) and correlation analysis (the Spearman coefficient) were used with respect to the only variable (the growth class). The multimodel inference approach were used when choosing the optimal multiple regression models (Burnham and Anderson, 2002).

RESULTS AND DISCUSSION

The changes in the morphological characteristics of trees in the urbanization gradient, i.e. the distinctions between three high-contrast groups of areas (suburban areas, city parks, and urban areas) proved insignificant. The trend towards decrease in the average tree diameter and height during the transition from the suburban tree stands to the city tree stands was ascertained to be weak and statistically insignificant (Table 2); moreover, the decreases in diameter by 2–6 cm and height by 1–4 m can be explained by the smaller average tree age in the residential area (Table 3).

Unlike the morphological characteristics, the change in the parameters of the vital tree status in the city indicates a well-marked negative change in proportion to the growth in the degree of urbanization. During the transition from the suburban areas to city parks and then to the urban areas, the tree damage index significantly grows. Urbanization is also accompanied by a decrease in needle crown density, which is due to the decrease in the average needle lifespan.

The average tree age (see Table 3) is weakly interrelated with the characteristics of the vital tree status;

Table 3. Matrix of the correlation coefficients (above the diagonal) and their levels of significance (below the diagonal) between the characteristics of pine tree stands ($n = 37$)

Parameter		Parameter									
		tree						tree stand			
		D	*H*	*A*	*I*	*F*	*L*	*N*	*B*	*M*	*T*
Diameter	*D*	–	+0.26	**+0.42**	**–0.36**	–0.24	+0.17	**–0.87**	–0.02	+0.14	–0.04
Height	*H*	0.119	–	**+0.33**	–0.01	–0.10	+0.02	–0.19	**–0.80**	**+0.52**	+0.15
Age	*A*	**0.011**	**0.048**	–	–0.17	–0.25	+0.30	–0.31	+0.04	+0.01	**+0.33**
Damage index	*I*	**0.028**	0.973	0.316	–	**+0.80**	**–0.78**	+0.21	+0.05	–0.15	+0.32
Degree of defoliation	*F*	0.148	0.553	0.141	**<0.001**	–	**–0.81**	+0.08	+0.08	–0.24	–0.01
Needle lifespan	*L*	0.305	0.901	0.068	**<0.001**	**<0.001**	–	+0.01	–0.04	+0.26	–0.02
Tree stand density	*N*	**<0.001**	0.249	0.059	0.202	0.647	0.948	–	+0.01	**+0.47**	+0.21
Growth class	*B*	0.927	**<0.001**	0.830	0.753	0.642	0.817	0.963	–	**–0.40**	–0.09
Living timber stock	*M*	0.415	**0.001**	0.956	0.364	0.150	0.127	**0.003**	**0.013**	–	+0.18
Share of deadwood in timber stock	*T*	0.814	0.386	**0.043**	0.054	0.935	0.908	0.211	0.579	0.300	–

Pearson's correlation coefficients, excluding coefficients belonging to the quality classes, for which, the Spearman's rank correlation coefficient are shown. Statistically significant coefficients and reliability levels are in bold.

therefore, as the results of the covariation analysis show (see Table 2), the distinctions in the average tree age between the urban and suburban tree stands modify the evidence of the urbanization effects only insignificantly. It is necessary to emphasize that the three characteristics of the vital tree status are all closely interrelated, which indicates that the described regularities in the pine damage in the urbanization gradient are objective. Therefore, the conclusion about the worsened vital status of the pine under the urban conditions is reliable.

Part of the characteristics of tree stands (total density, growth class, and share of deadwood) are not interrelated with the level of urbanization. In the meanwhile, the timber stock significantly decreases in the city, which indirectly indicates the decrease in phytomass of the tree tier. This effect is significant both in the absolute expression (from 365–577 m^3/ha in suburbs to 328–534 m^3/ha in city parks and to 251–440 m^3 in the residential area; the distinctions between the extreme variants are 20–30%) and regarding the statistical reliability of the conclusion. The decrease in the timber stock takes place independently of the change in the average tree age (Tables 2 and 3).

Proceeding from the obtained data, we can suppose that the 20–30% decrease in the timber stock is caused by the summation of insignificant negative effects of the change in the investigated characteristics of tree stands. This supposition is supported in particular by the results of the multiple linear regression analysis that connects the total timber stock with the average tree sizes and tree stand density (using the standardized partial coefficients):

$$M = 1.43N + 0.97D + 0.55H. \qquad (1)$$

The obtained regression model (see the designations of the variables in Table 2) is characterized by a fairly high quality ($R^2 = 0.83$; $P \ll 0.001$; the partial coefficients are statistically significant at the levels $P < 0.01…0.001$), but it is somewhat trivial, since it "imitates" the method for estimating the value of the timber stock. According to the obtained equation, the timber stock (M) in a tree stand grows in proportion to the stand density (N) increment, as well as in proportion to the growth in the average tree diameter (D) and height (H). Moreover, the stand density increment influences the value of the stock most strongly and the tree height increment affects it to the least extent.

In order to ascertain whether the total timber stock is affected by the change in the sanitary status of individual trees, the procedure for selecting the optimal predictor combination was applied using the Akaike information criterion (AIC) for the case of linear additive models. The best accuracy/simplicity ratio was found to be possessed by the following regression model (which uses the standardized partial coefficients):

$$M = 1.39N + 0.94D + 0.60H - 0.17A - 0.4I. \qquad (2)$$

The quality of this equation in comparison with the "trivial" model (1) is somewhat higher ($R^2 = 0.86$; $P \ll 0.001$; the partial coefficients of the variables N, D, and H are significant at the level $P < 0.01…0.001$; the coefficient of the variable A is significant at the level $P = 0.037$, and that of the variable I is significant at the level $P = 0.074$). In comparison with the trivial model, model (2) is much better: the ratio of the Akaike weights is 0.50/0.09 = 5.60. Other combinations of additional predictors (either only the tree age (A) or only the damage index (I)) do not give a significant advantage in comparison with model (1): the ratio of weights is 1.78 and 2.74, respectively. The remaining models are much worse than model (1) if they do not simultaneously include three major predictors (*N*, *D*, and *H*).

The major determinants of the timber stock (tree stand density, diameter, and height) are present in Eq. (2) with the same signs and with the coefficients, which are very close to those of Eq. (1). The additional presence of the variable "average tree age" as a predictor with the negative sign confirms that the age-dependent decrease in the tree-stand density due to the activation of dying away and thinning of stands has the greatest consequences for the dynamics of the stock level (see Table 3: the partial correlation is negative between age and density ($r = -0.31$) and positive between age and share of deadwood ($r = +0.34$)). Apparently, the tree-size increment in the growth process (the correlation with age is $r = +0.42$ and $r = +0.33$ for diameter and height, respectively) does not compensate for the existent decrease in the tree-stand density. The index of integral tree damage is the only variable related to the vital status of trees from amongst the stock predictors in Eq. (2). This variable is included in the equation with the negative sign, i.e., worsened sanitary status leads to the decreased timber stock. Meanwhile, there is no escape from noting a very small direct contribution of this variable: about 2 of 86% of the total variance explained by Eq. (2).

The obtained materials can be interpreted as follows. The vital status and morphological characteristics of trees in the park zone of Yekaterinburg on average change very slightly in comparison with the suburban forests. The significant changes in the status of individual trees and an entire tree stand are registered in tree stands inside living quarters (*TPs* nos. 44, 46, 47, 53, and 55). From amongst the indicators of the organism level, significant changes are immanent only to the parameters of the vital status rather than to the morphometric characteristics of individual trees. This conclusion is in good agreement with the results of other authors, who showed that the significant radial increment of coniferous trees (up to 30–40%) can be supported at their high defoliation (Schmid-Haas, 1989; Beyschlag et al., 1994). This can be caused by the improved conditions of crown illumination and high photosynthetic activity of young needles, which ultimately ensures an increment comparable with the increment of healthy trees. However, being summed, the insignificant changes in the average tree diameters and heights, as well as tree-stand density, determine the established decrease in the total timber stock by 20–30% in the city tree stands.

It is necessary to note that even the established decrease in the stock cannot be considered critical. It is partially compensated for at the cenotic level by reconstructions due to the growth of shrubs under the pine canopy and the second tier of deciduous species (Zolotareva et al., 2011; Tolkach and Dobrotvorskaya, 2011). On the whole, the level of viability of mature pine trees in a large industrial city remains rather high despite the worsened sanitary status of trees and activation of their damage by phytopathogenic fungi (Veselkin et al., 2013). An analysis of the data indicates that mature pine tree stands of the city are in the satisfactory status and retain the capability to perform environment-stabilizing functions. This does not mean that forests in the territory of Yekaterinburg are not in significant danger. The assertion about relative resistance is correct only with respect to the components of the complex urbanization impact, such as pollution and recreational effects. The fragmentation of the territory due to direct anthropogenic damages (cutting, road arrangement, construction, etc.), as well as reforestation processes (including seed bearing and the formation of viable undergrowth), are apparently critical for the forest vegetation in an urban environment (Repshas, 1994; *Ekologicheskoe*..., 2009; Tolkach, 2011; Tolkach and Dobrotvorskaya, 2011).

CONCLUSIONS

The major morphometric characteristics and indicators of the sanitary status of the Scots pine and tree stands do not significantly change in comparison with the suburban forests. In other words, the naturally determined regional level of the total productivity of pine tree stands does not change in the parks. In the tree stands inside the residential area, the sanitary status of trees reliably worsens, and the needle lifespan and timber stock of living trees decrease. According to the built multiple regression model, the observed decrease in the timber stock in the urbanized areas is caused by summation of small changes in the tree-stand density, morphometric characteristics of trees, and their vital status. Meanwhile, the worsened sanitary status of trees determines only a small share of timber stock variability: about 2% of 86% of the total variance explained by the model. On the whole, mature pine stands in the territory of a large industrial city can be durably resistant to negative environmental impacts, such as pollution and recreational effects.

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