ISSN 1995-4255, Contemporary Problems of Ecology, 2016, Vol. 9, No. 7, pp. 844–852. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © S.A. Shavnin, D.V. Veselkin, E.L. Vorobeichik, V.A. Galako, V.E. Vlasenko, 2015, published in Lesovedenie, 2015, No. 5, pp. 346–355.

Factors of Pine-Stand Transformation in the City of Yekaterinburg

S. A. Shavnin[a], D. V. Veselkin[b, *], E. L. Vorobeichik[b], V. A. Galako[a], and V. E. Vlasenko[a]

[a] *Botanical Garden, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620144 Russia*

[b] *Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, Yekaterinburg, 620144 Russia*

**e-mail: denis_v@ipae.uran.ru*

Received December 2, 2014

Abstract—The relationships between the health of *Pinus sylvestris* trees and stands and the levels of anthropogenic stress and fragmentation of habitats have been studied based on the example of pine stands of natural origin in Yekaterinburg and its vicinity (48 sampling plots located at different distances from the center of the city). The distances from the city center and from the boundary of a built-up area to a sampling plot and the population density around this plot are taken to characterize the level of anthropogenic stress. The area and perimeter of a forest site; the distance from the boundary of a sampling plot to the forest edges; and the shape of forest edges are used to characterize the level of fragmentation of habitats. We have found that the average morphological metrics of trees have slight changes, while the traits of tree health are significantly altered under urban environment. The overall performance of stands decreases by 22–35% in the urbanization gradient. The health of stands is most substantially influenced by the forest-site area. The population density around sampling plots and the distance of these plots from the megalopolis center have a lower effect on the health of trees and stands. Fragmentation of forests in the city leads to a decrease in the size of forest sites, which causes a decrease in wood stocks and the diameter and height of trees and the deterioration of their health. The lowest area of the forest to make it sustain an urban environment is about 30 ha. The untransformed core of forest is located no less than 70 m from the forest edge.

Keywords: Scots pine, urbanization, recreation, urban forests, productivity, habitat fragmentation, edge effects

DOI: 10.1134/S199542551607009X

Forests and tree plantations in cities are an important component of the urban environment. The growing attention to their study, including studies in Russia (Burova and Feklistova, 2007; Shergina and Mikhailova, 2007; *Ekologicheskoe sostoyanie*..., 2009; Rysin, L.P. and Rysin, S.L., 2012), is due to the fact that the knowledge of mechanisms of transformation and resistance of urban forests serves as the basis for controlling their environmental and social functions. The importance of studying urban stands is confirmed by the emergence of a special area of forestry, namely, urban forestry (Konijnendijk et al., 2006; McPherson, 2006; Rysin, L.P. and Rysin, S.L., 2012).

Among the basic components of the integrated factor of urbanization that influence plants, the effects of various forms of chemical pollution (Chernen'kova, 2002; Shergina and Mikhailova, 2007; et al.) and recreation (especially with respect to understory) (Malmivaara et al., 2002; Burova and Feklistova, 2007; et al.) and the sanitary state of trees and their renewal (Lebedev, 1998; Selochnik, 2008; *Ekologicheskoe sostoyanie*..., 2009; Tolkach and Dobrotvorskaya, 2011; Veselkin et al., 2013), have been most extensively studied. Another important aspect of urbanization—fragmentation of habitats—has been studied less in detail with respect to vegetation.

Fragmentation of natural landscapes is considered to be an important negative result of human activity and is taken into account both during the analysis of its effects and during planning of environmental protection activities (Murcia, 1995; Harper et al., 2005; Zagurnaya, 2008; Morozova and Tsarevskaya, 2010). One of the main consequences of fragmentation is expressed in an increase in the length of edges between different types of communities and, accordingly, in the area of ecotones (Harper et al., 2005) in which the microclimate is substantially transformed and the diversity and functioning of the biota is altered (Saunders et al., 1991; Murcia, 1995; Laurance et al., 1997, 1998; Harper et al., 2005).

Fragmentation is most critical for forests when compared with other types of vegetation, since it leads to considerable changes in microclimate and intra- and interspecific competition. The recognition of the importance of taking into account the edge effect for forest communities has been reflected in the fact that the absolute value of the planting area is often indicated among the forest criteria as a type of vegetation (Belov, 1983; Vidal et al., 2008). Forest fragmentation is most often analyzed as a factor influencing other objects: herbaceous plants and lichens and invertebrate and vertebrate animals. Estimates of fragmentation consequences for the health of trees and stands themselves are not as numerous; however, they are not occasional. Thus, the review of 1995 (Murcia, 1995) analyzed the results of 24 studies on this problem, and the review of 2005 (Harper et al., 2005) analyzed 44 studies; fragmentation effects were studied approximately with the same completeness in forests of different natural zones, and the density of forest stands and crown cover and the abundance of understory plants were most often taken into account compared to other indicators.

The investigation of fragmentation is particularly important under urbanization conditions, since urban forests are surrounded by an artificial urban environment, rather than by forestless spaces of natural genesis. In addition, fragmentation under urban conditions is most often combined with a substantial decrease in the average area of fragments, rather than being just the splitting of the entire woodland into fragments, which sharply increases the edge effects. It is recognized that the range of an edge effect for biota directly depends on the range of abiotic factors, first and foremost, on solar radiation, temperature, and the flow of aerosols—including pollutants (Harper et al., 2005; Weathers et al., 2001). Therefore, it can be assumed that forest fragmentation in a city increases the negative impact of direct urbanization effects (i.e., different forms of pollution and recreation) on the forest stand. Meanwhile, to the best of our knowledge, the effects of fragmentation of forest stands with respect to tree vegetation under urban conditions have not been specifically studied. This determined the purpose of our work, i.e., to perform an analysis of the state of trees and stands of Scots pine (*Pinus sylvestris* L.), depending on their arrangement in urbanization and fragmentation gradients, based on the example of a large industrial city (Yekaterinburg). First of all, we thought to find informative predictors, i.e., such metrics of sites which would better indicate the health of forest stands in an urban environment. In addition, we were interested in assessing the interaction between urbanization and fragmentation.

MATERIALS AND METHODS

Study area. Yekaterinburg is a large industrial city in the Middle Urals with an area of 49800 ha and a population of about 1.4 million people; it is located in the southern taiga district of the Trans-Ural hilly–piedmont province (Kolesnikov, 1973). The surrounding areas are dominated by pine forests of natural origin on sod–podzolic soils and burozems.

The area of Yekaterinburg is considered severely polluted (Sturman, 2008) both due to the presence of a great number of industrial enterprises and to the effect of a high density motor transport network. In 2010–2012, atmospheric emissions (sulfur, carbon, and nitrogen compounds; mineral dust; and heavy metals) were 190000–215000 t per year, of which nitrogen compounds were about 10000 t. The largest contribution to atmospheric pollution (up to 85%) is made by urban motor transport (Sturman, 2008; *Gosudarstvennyi doklad*..., 2011, 2013). The average daily concentrations of NO_2 are up to 20–30 μg per m^3 in the center of the city and 15–20 μg per m^3 in peripheral residential areas (Antropov and Varaksin, 2011); the maximum concentrations of Cu, Ni, Pb, Cr, Zn, and Cd and Mn in the soil exceed the background values by 58, 20, 18, 8, 6, and 3 times, respectively (*Gosudarstvennyi doklad*..., 2011).

Historically, Yekaterinburg sprouted up near a metallurgical plant about 300 years ago (in 1723) and was further spread from the center to the periphery. Therefore, the general configuration of the city is close to the radiosymmetrical configuration (Yemlin, 2006); accordingly, the central areas are the most transformed, while the peripheral areas are the least transformed. Almost one-third (15300 ha) of the area of Yekaterinburg is occupied by forest parks and urban forests; most of them are of natural origin. The forest parks are generally located at the periphery of the city and usually border on adjacent forests or agricultural lands.

Location of sampling plots. This work is based on materials obtained in 2009–2012 during the survey of 48 sampling plots, which were located in three groups of stands (Fig. 1): (1) in the urban built-up area (based on the history of urban development, the sites were isolated from the main forest park ring of the city in the 1970s–1980s), (2) in the urban forest parks (Yugo–Zapadny Park, Lesovody Rossii Park, and Kalinovski Park and Arboretum of the Botanical Garden, Ural Branch, Russian Academy of Sciences), and (3) in suburban forests at a distance of 8–10 km from the city boundary. Therefore, we compare three groups of stands further referred to as intraurban (n = 18; *sampling plots* 41–49, 51–56, and 57–59), forest park (n = 23; *sampling plots* 1–6, 13–18, and 21–31), and suburban (n = 7; *sampling plots* 7–12 and 60).

All sampling plots are selected taking into account the following criteria: (1) natural origin of the forest stand; (2) the share of pine stock is over 70% in the forest stand; (3) the mean age is no less than 90 years (generally, 6th–8th age classes); (4) the stands are confined to transient topographic features (the altitude range is 265–325 m above sea level); (5) the type of forest growing conditions corresponds to the forb group of forest types; and (6) there are no new and/or widespread and/or intentional anthropogenic disturbances of the soil cover (roads and excavations), forests (fires and cuttings), and groun vegetetion layer (haying). In other respects, we sought to provide the maximum range of both distances to the center of the city and areas of forest sites during the establishment of sampling plots.

The sampling plots in suburban areas and forest parks were laid according to OST 56-6983 with an area of 0.3 ha (50 × 60 m); the number of trees of the main stand was 70–190 specimens per sampling plot. In

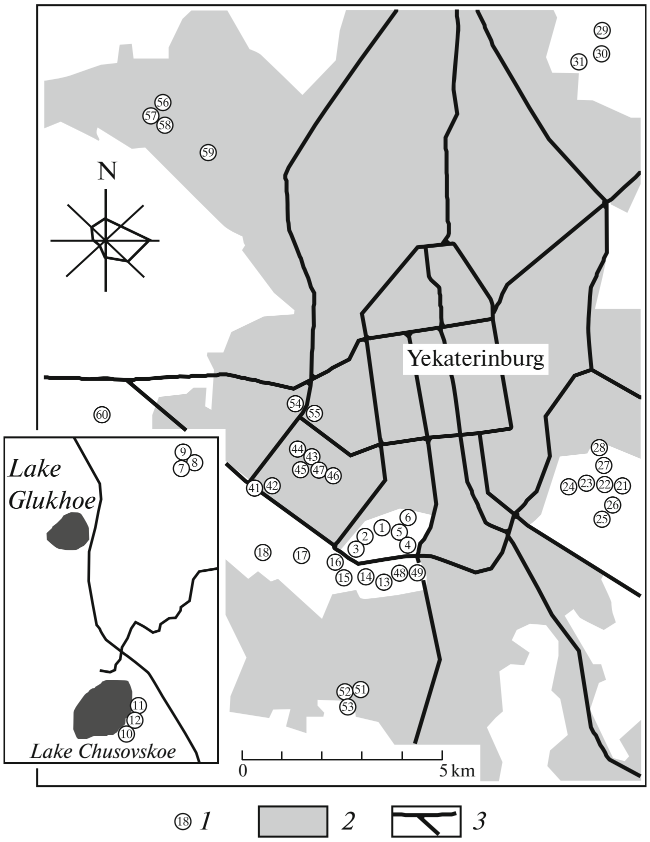

Fig. 1. Wind diagram and layout of sampling plots (*1*) in the built-up area in Yekaterinburg (*2*), in forest parks, and in the vicinity of the city with respect to main transport routes (*3*). The suburban site in the area of lakes Glukhoe and Chusovskoe (inset) is located 8–10 km to the west of the boundary of the built-up area.

intraurban areas, the studies were carried out in forest sampling sites (Anuchin, 1982) with an area of 0.0625 ha (25 × 25 m); the number of trees was 10–40 specimens per sampling site.

Characteristic of sampling plots. For each sampling plot, we estimated two groups of parameters that characterized (1) the level of anthropogenic stress and (2) the level of habitat fragmentation.

The following parameters were used as characteristics of *the level of anthropogenic stress*: (a) distance from the city center to the sampling plot, (b) distance from the boundary of the built-up area to the sampling plot, and (c) population density around the sampling plot. The estimates were obtained using the free 2GIS-Yekaterinburg geoinformation system. To calculate the population density around a sampling plot, we used the data on the presence of preschools (in accordance with the average values for Yekaterinburg, one preschool covers 3300 persons), schools (10100 persons), and pharmacies (2700 persons) within a radius of 1 km from the sampling plot under consideration (equivalent to 12–18 min on foot).

The following parameters were used as characteristics of *the level of habitat fragmentation*: (a) area of the forest site, (b) perimeter of the forest site, (c) distance from the edge of the sampling plot to the forest edge (i.e., the depth of location of the sampling plot with respect to the forest edge), and (d) shape index of forest edges (Paton index used in landscape ecology, i.e., the ratio of the perimeter of the site to the length of the circumference of the circle whose area is equal to the area of the site). These parameters were determined according to the space images extracted from the free Google Earth system. The images were brought to the scale of 1 : 10000 to 1 : 12000 and then analyzed. The distance of 50 m (two mean heights of a tree of the main stand) was assumed to be discontinuities specifying the forest edges.

Assessment of the health of trees and forest stand. In each sampling plot, the complete numeration of trees was performed, during which we measured the trunk diameter at a height of 1.3 m using a caliper with an accuracy of 1 cm and height using an electronic altimeter with an accuracy of 0.1 m. The tree category included individuals with the diameter of over 8 cm at a height of 1.3 m. The age was determined by core samples that were taken with an increment borer from six to ten model specimens per each sampling plot that were selected proportionally to the representation of trees of different size classes. The health of trees was visually assessed by standard methods: the damage class was determined for each tree according to a 6-point scale (*Metodika organizatsii*..., 1995; Alekseev, 2003); by averaging their values, we obtained the tree damage index. Also, we determined the level of defoliation (*Sanitarnye pravila*..., 1998) and the average lifetime of needles (*Manual*..., 1994) for each tree.

The statistical analysis was performed in the STATISTICA 6.0 software (StatSoft Inc.). For the factor analysis, the variables whose distribution was deflected from the normal one were presented in the logarithmic form: $x' = ln(x)$ or $x' = ln(x + 1)$ (for variables with zero values) or $x' = ln(x + |min| + 1)$ (for variables with negative values). Since the basic assumptions of parametric tests were usually not implemented for verifying statistical hypotheses, nonparametric methods, namely, the Kruskall–Wallis test (H) and the Spearman correlation coefficient (r_S), were used. The regression dependences were approximated using a logistic equation; the coordinates of critical points were analytically determined through the equation coefficients.

RESULTS

Characteristics of habitats. As could be expected, the sites arranged in the order of increasing the level of urbanization contrast against each other by their position to the center of the city and to the boundaries of the built-up area (Table 1). Estimates of the population density around the sampling plots that were

Table 1. Characteristics of sampling plots in different groups of stands

Parameter	Forest groups ($m \pm SE$)			Significance of differences*	
	suburban forests (n = 7)	forest parks (n = 23)	intraurban forests (n =18)	H	P
Metrics of the level of anthropogenic stress					
Distance from the sampling plot, km					
to the city center	17.40 ± 1.66	5.76 ± 0.14	6.24 ± 0.42	16.37	<0.001
to the boundary of the built-up area	8.94 ± 1.54	−3.25 ± 0.32**	−2.75 ± 0.33	17.75	<0.001
Population number (thousand persons) around the sampling plot based on the number of***					
preschools	0	12.3 ± 2.4	28.8 ± 3.4	10.61	0.001
schools	0	10.0 ± 1.3	27.4 ± 3.7	15.02	<0.001
pharmacies	0	7.9 ± 1.9	28.9 ± 4.2	14.24	<0.001
mean	0	10.0 ± 1.7	28.4 ± 3.5	14.62	<0.001
Metrics of the level of habitat fragmentation					
Area of the forest site, km^2	2.57 ± 0.52	2.75 ± 0.49	0.05 ± 0.02	28.98	<0.001
Perimeter of the forest site, km	10.26 ± 1.68	7.08 ± 0.64	0.79 ± 0.15	33.20	<0.001
Depth of location of the sampling plot revative to forest edges, km	0.17 ± 0.08	0.36 ± 0.08	0.02 ± 0.01	27.75	<0.001
Shape index of forest edges, conventional units	1.86 ± 0.08	1.46 ± 0.06	1.39 ± 0.06	9.65	0.008

* Here and in Table 3, the values of the Kruskall–Wallis test (H; $dF = 2$; and $n = 48$) and its level of significance (P) are given; m is the arithmetical mean; SE is the standard error.
** The minus sign indicates the location of forest ranges within the built-up area.
*** The estimate of the significance of differences in the population number between different groups of stands did not take into account sampling plots in the suburban forest ($dF = 1$; $n = 41$).

obtained using different predictors were very similar to each other. In addition, all three predictors are closely interrelated for urbanized sites (forest parks and intraurban sites) ($r_S = +0.78...+0.88$; $n = 41$; and $P < 0.001$); therefore, the averaged estimates of the population density were further used. The average population density is 2.5–3.5 times lower around the sampling plot in forest parks than that in the urban built-up area and is equal to zero in some of them.

The area of forest sites in the city is 25–100 times lower than that in the suburban zone (0.02–0.1 km^2 vs. 2–4 km^2). The average perimeter in the city also decreases by an order of magnitude. As opposed to what was expected, the shape index of forest edges in the city was significantly lower than that in the vicinity of the city. In other words, the configuration of edges of small forest fragments and forest parklands in the city is more approximated to the circle than the configuration of forest sites outside the city. Due to a decrease in the area of sites in the built-up area, the boundary of sampling plots are only 0–25 m away from the forest edges; i.e., they often coincide with each other.

The structure of correlation between the predictors was studied by principal components extraction (Table 2). Two factors, that are orthogonal to each other by definition, are rather clearly distinguished, which together explane more than 80% of variance. The first factor includes distances to the city center and to the boundary of the built-up area, and the second factor includes the area and perimeter of the site and the depth of location of the sampling plot relative to the woodland edge. This structure of correlations between predictors makes it possible to interpret the first factors as a characteristic of the level of urbanization, while the second one can be interpreted as the characteristic of the level of fragmentation of stands. The population density is included in both main components with signs opposite of other predictors. Based on the revealed structure of correlations, three key metrics—distance to the city center, area of the site, and population density—were selected for further analysis.

Health of trees and stands. The effect of urbanization on the average morphological metrics of trees is poorly pronounced. When suburban forests shifted to intraurban ones, the average diameters decrease by 3–7 cm and the average heights decrease by 2–5 m (Table 3). To some extent, these changes can be explained by the lower mean age of trees in the city.

Unlike morphological metrics, health traits show a clearly pronounced damage of trees and forest stand due to the urbanization effect. Outside the city, the average index of tree health varies in the range of 2.0–

Table 2. Structure of correlations between the metrics of sampling plots

Parameter	Factor loadings*	
	factor 1 (urbanization)	factor 2 (fragmentation)
Metrics of the level of anthropogenic stress		
Distance from the sampling plot to the city center**	+0.964	+0.092
Distance from the sampling plot to the boundary of the built-up area**	+0.899	+0.092
Population number around the sampling plot	–0.663	–0.579
Metrics of the level of habitat fragmentation		
Area of the forest site**	+0.168	+0.957
Perimeter of the forest site**	+0.347	+0.846
Depth of location of the sampling plot relative to forest edges	–0.275	+0.908
Shape index of forest edges	+0.686	–0.184
Proportion of total variance	0.41	0.41

* Varimax-rotation was used.
** The parameter was transformed by logarithmation.

Table 3. Tree and forest characteristics in different options of stands

Parameter	Options of stands			Significance of differences	
	suburban forests	forest parks	intraurban forests	H	P
Mean characteristics of the health of trees					
Diameter, cm	42 ± 2	42 ± 2	37 ± 2	6.11	0.047
Height, m	27 ± 1	27 ± 1	24 ± 1	5.39	0.068
Age, years	128 ± 6	132 ± 4	116 ± 4	8.32	0.016
Damage index, points	2.5 ± 0.1	2.8 ± 0.1	3.1 ± 0.1	15.39	<0.001
Level of defoliation, %	38 ± 3	40 ± 1	48 ± 1	18.19	<0.001
Lifetime of needles, years	2.3 ± 0.1	2.1 ± 0.1	1.9 ± 0.1	21.22	<0.001
Stand characteristics					
Stand density, spec. per ha	323 ± 37	341 ± 35	343 ± 38	0.02	0.990
Quality class, point*	II	II (I–IV)	III (I–IV)	5.26	0.072
Stock of living tree wood, m^3 per ha	468 ± 29	470 ± 13	337 ± 24	17.99	<0.001

* The mode and range of values are given for the quality of locality.

3.0 points, while in forest parks and in the built-up area it varies from 2.5 to 4.0 points, with the defoliation level increasing from 25–50 to 40–55% and the average lifetime of needles decreasing from 2.0–2.7 to 1.8–2.0 years. A strong correlation is observed between all characteristics of the health of trees ($|r_S|$ = 0.78...0.89; $n = 48$; and $P < 0.001$), which shows their unidirectional change in the urbanization gradient.

Despite the constancy of the value of stand density in sampling plots, the total performance of forest stand decreases in the urbanization gradient. This is confirmed both by an increase in average quality points and, mainly, by a decrease in wood stock. The latter statement is substantial in absolute terms (the differences between the outermost group are 22–35%) and is statistically significant (Table 3).

The correlations between the characteristics of sampling plots and the health of trees and forest stand cannot be recognized to be very strong: the highest values of $|r_S|$ is in the range 0.55–0.65; however, on average, they are markedly lower (Table 4). Nonetheless, the large sample sizes determines the statistical reliability of estimates of correlation coefficients.

The largest number of significant coefficients was established with respect to the area of the site (eight of nine) and the population density (five of nine). The distance from the sampling plot to the city center is associated only with the mean age of trees. The analogical order is for the mean values of the relationship

Table 4. Relationship between the characteristics of tree and stand health and the key metrics of sampling plots ($n = 48$)

Characteristics of trees and stands	Metrics of sampling plots					
	distance from the city center		area of the forest site		population density	
	r_S	P	r_S	P	r_S	P
Diameter	–0.02	0.914	+0.34	0.016	–0.42	0.003
Height	+0.05	0.758	+0.30	0.037	–0.10	0.510
Age	–0.37	0.009	+0.30	0.040	–0.15	0.306
Damage index	–0.25	0.086	–0.51	<0.001	+0.56	<0.001
Deforliation level	–0.10	0.482	–0.65	<0.001	+0.59	<0.001
Lifetime of needles	+0.12	0.417	+0.53	<0.001	–0.56	<0.001
Stand density	+0.07	0.646	+0.01	0.937	+0.07	0.639
Quality class	–0.27	0.071	–0.32	0.030	+0.13	0.372
Stock of living tree wood	+0.18	0.215	+0.66	<0.001	–0.49	<0.001
Mean value of $\|r_S\|$	0.16		0.40		0.34	

Spearman correlation coefficients (r_S) and its significance (P) are given.

strenght: the highest values of $|r_S|$ are observed for the site area, while the lowest values are recorded for the distance to the city center. Therefore, among the above-considered metrics of sampling plots, the area of the site can be considered the most important health index of forest stand with respect to the entire complex of traits. The population density in the immediate vicinity of the sampling plots is closely related to the health of trees, rather than to their morphological metrics and the integral characteristics of forest stands.

Form of relationship between fragmentation and health of stands. The analysis of the correlation between the area of a forest site and the health of stand allows us to reveal the lowest area of forest to make it sustain the urban environment. The shape of the curve approximating the relationship between the wood stock and the area of the site indicate some nonlinearity of dependences (Fig. 2a): $R^2 = 0.53$ for the linear regression and $R^2 = 0.56$ for the logistical regression. The nonlinearity of the dependence of wood stock on the distance to the forest edge is more pronounced (Fig. 2b): $R^2 = 0.49$ for the linear regression and $R^2 = 0.56$ for the logistical regression.

Although the difference in accuracy is small between the linear and nonlinear models, the use of the logistic regression makes it possible to determine the thereshold values that mark transitions between stationary and nonstationary regions of the system state. Of particular interest is the abscissa of the upper critical point, which was 30 ha for the dependence of wood stock on the area of the site. The analysis of the dependence of wood stock on the distance of the sampling plot to the edge made it possible to determine the critical depth of location of the plot, which is 68 m.

DISCUSSION

The characteristics of trees in Yekaterinburg forest parks are hardly different from the characteristics of trees in suburban forests. Substantial changes in the health of individual trees and the entire forest stand were recorded only within built-up areas. The effect of urbanization largely transforms the health parameters; at the same time, the decrease in the integral parameter of the health of stands, i.e., wood stock, by 20–30% cannot be considered critical, despite the deterioration of the sanitary state of trees and activation of their infestation by phytopathogenic fungi (Veselkin et al., 2013).

The revealed relationships between the characteristics of sampling plots and the health of stands were opposite to those we expected. Initially, we expected to reveal the existence of a strong relationships between the forest state and the population density and the distance to the city center. This hypothesis was based on the rather logical assumption that the number of people living in the vicinity of the sampling plot is closely related to the visiting intensity of the site, i.e., to the level of direct recreation load and other components of anthropogenic press, e.g., to the traffic intensity. In addition, it would be logical to assume that the level of atmospheric pollution and the duration of anthropogenic impact decrease with distance from the megalopolis center. However, the revealed relationships between the level of urbanization and the health of stands were rather weak. This suggests the presence of another, more important external factor determining the state of urbanized forests.

The health of trees and the entire forest stand is most closely related to the fragmentation of woodlands, first and foremost, to the area of the site. The larger the area

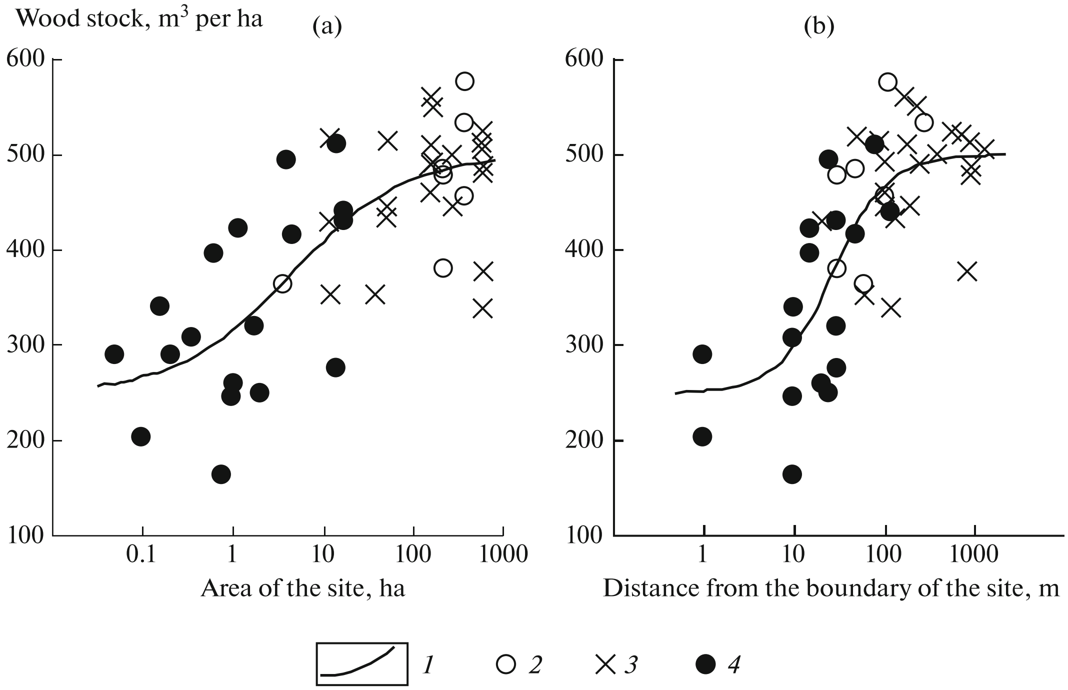

Fig. 2. Dependence of wood stock on the area of the forest range (a) and the depth of location of the sampling plot with respect to the edge of woodland (b). (*1*) Lines of approximation by equation. Sites: (*2*) suburban sites, (*3*) forest parks, and (*4*) urban sites.

of the site, the better the forests are able to perform habitat forming functions (due to an increase in morphological metrics of trees, the improvement of their health, and the growth in wood stock). According to the our estimates, in Yekaterinburg, the value of about 30 ha can be considered the lowest area of the pine stand to maintain the sufficient stability of its integral productivity (Fig. 2). Forest fragments with this area are absent in the built-up area and presented only in forest parks and outside the city. Among other things, this makes it possible to predict further degradation of urban stands in the future. Edge effects of environmental transformation in Yekaterinburg are no longer observed at a distance of about 70 m deep from the forest edge. In most cases, the area of fragmented forest ranges in the built-up area does not allow the fulfillment of this condition; therefore, forests in the city can be considered as continuous ecotones. It should be emphasized that the area of the forest site and the distance to the core of the forest cannot be considered as completely independent parameters (especially when the absolute values of the area of forest sites are small). They actually characterize the same phenomenon from different perspectives and can be considered interchangeable when they are used as predictors for the health of stands.

To explain the revealed relationships between the area of a forest site and the health of the forest, we propose two interpretations. On the one hand, fragmentation, i.e., the splitting of large continuous woodlands into fragments, especially in combination with a decrease in area of fragments, can be assumed to be a self-contained factor that is functionally associated with the health of individual trees and the entire forest stand. On the other hand, fragmentation can be correlated with other components of the anthropogenic press that are more difficult to be formalized, such as recreation load, pollution, and duration of urbanization effect. The first interpretation is confirmed by a large volume of data on the direct negative effects of forest fragmentation in the absence of other forms of anthropogenic impact (Saunders et al., 1991; Murcia, 1995; Laurance et al., 1997, 1998; Harper et al., 2005). However, it appears almost impossible to correctly distinguish the pure effect of urbanization and fragmentation on urban forests without special studies. Moreover, both interpretations can be simultaneously true, since the adverse impact of different factors, including the impact of atmospheric pollutants, mainly covers the edges of stands and their peripheral sites (Weathers et al., 2001; Harper et al., 2005). Conparts sequently, it is more important to search for the relationship between different mechanisms of negative impact of factors in urban environment rather than choose “the only true” interpretation.

Starting from classical works of Morozov (1970), the formation of a specific cenotic environment only at some distance from the edge of woodland is present as the main criterion in definitions of the forest as a type of ecosystem (Anuchin, 1982; Belov, 1983). The requirement for levelling edge effects is established in regulatory documents (OST 56-69-83), according to which taxation sampling plots should be placed no more than 100 m from the forest edge, forest margins, roads, etc. In fragmented tropical rain forests of the Amazonian region, the distance of 80–90 m from the forest edge was the lowest for the damage of trees, the distance of 300–400 m was the lowest for the tree mortality (Laurance et al., 1997), and the distance of 100 m was the lowest for changes in the aboveground biomass (Laurance et al., 1998). Although there is a considerable variability in the distance to the edge of forest in which deviations of forest characteristics from the background level are recorded, the modal values of critical distances is in the range 30–70 m for different forest indices (Murcia, 1995; Harper et al., 2005). Edge effects are observed at an average distance of 30–40 m in boreal forests in Europe and at an average distance of 20–30 m in dark-coniferous forests in North America. Therefore however, the variability of the values is significant for different parameters of stands (Harper et al., 2005). Therefore which makes it is difficult to compare our results with literature ones and does not allow us to correctly discuss the issue on the extent to which urbanization modifies the degree of manifestation of edge effects associated with fragmentation. It should be noted that the lowest distances that are close to those found by us are given for the city of Moscow: the health of pine, birch, oak, and aspen is close to the background level only at a distance of more than 60–100 m from the Moscow Ring Road, while “in the strip with a width of 40–60 m that contacts this road, total death of forest can be expected” (Rysin, L.P. and Rysin, S.L., 2012). The similarity of available estimates of the width of buffer forest strips suggests that the stability of the regime of cores of forest ecosystems is provided by a marginal strip with a width of 50–100 m, and this distance is presumably not very depend on the regional and species specificity of tree vegetation or on the option of anthropogenic impacts.

CONCLUSIONS

The area of woodland (or its fragment) can be considered the most informative determinant of the health of separate individuals and pine forest stands in urban environment. Forest fragmentation in the built-up area of an industrial megalopolis leads to the deterioration of the health of trees and a decrease in their average diameter and height and wood stock, i.e., a decrease in the biological productivity of stands and, accordingly, in the habitat-forming ability. The population density around the site or its distance from the center of the megalopolis has a considerably lower effect on the health of trees and forest stands.

For Yekaterinburg conditions, the lowest area of the forest to make it capable of maintaining the basic functional parameters is about 30 ha. The marginal strip, which plays the buffer role and provides the relative stability of environment in the core of forest, is about 70 m from the edge of woodland. These estimates are likely to be also true for other large cities, at least for those located in forest zone. Accordingly, they can be used in practical activities for increasing the sustainability of urban forests.

Therefore, the inability of small fragments of forests in the urban environment to provide the existence of stable internal cenotic environment can be one of the primary causes of their degradation. This explanation does not reject the generally discussed arguments on physiological (Chernen’kova, 2002; Shargina and Mikhailova, 2007), population (Repshas, 1994; *Ekologicheskoe sostoyanie*..., 2009; Tolkach and Dobrotvorskaya, 2011), or ecological (Lebedev, 1998; Shergina and Mikhailova, 2007; Selochnik, 2008; Veselkin et al., 2013) mechanisms of degradation of urban forests; however, it focuses on the importance of taking into account the spatial patterns of sites in urban environment.

Our results show that it is necessary to pay careful attention to the arrangement of sampling plots with respect to woodland edges in the analysis of research results in urban forestry. Extraordinary problems concerning the selection of sampling plots that are comparable by their spatial metrics are specifically characteristic of cities where it may be particularly difficult to distinguish direct (pollution and recreation) and indirect (invasions of pathogens and microclimate change) effects due to the considerable level of fragmentation of stands.

ACKNOWLEDGMENTS

This study was supported by the Integrated Research Program of the Ural Branch, Russian Academy of Sciences, project nos. 12-I-4-2057 and 15-12-4-32.

REFERENCES

Alekseev, A.S., *Monitoring lesnykh ekosistem (*Monitoring of Forest Ecosystems), St. Petersburg: Lesotekh. Akad., 2003.

Antropov, K.M. and Varaksin, A.N., Evaluation of nitrogen dioxide atmospheric air pollution in Yekaterinburg by land use regression methods, *Ekol. Sist. Prib*., 2011, no. 8, pp. 47–54.

Anuchin, N.P., *Lesnaya taksatsiya* (Forest Inventory), Moscow: Lesn. Prom-st, 1982.

Belov, S.V., *Lesovodstvo* (Forestry), Moscow: Lesn. Prom-st, 1983.

Burova, N.V. and Feklistova, P.A., *Antropogennaya transformatsiya prigorodnykh lesov* (Anthropogenic Transformation of Vicinity Forests)*,* Arkhangelsk: Arkhangelsk. Gos. Tekh. Univ., 2007.

Chernen’kova, T.V., *Reaktsiya lsenoi rastitel’nosti na promyshlennoe zagryaznenie* (Reaction of Forest Vegetation on Industrial Pollution), Moscow: Nauka, 2002.

Ekologicheskoe sostoyanie prigorodnykh lesov Krasnoyarska (Ecological Status of Vicinity Forests of Krasnoyarsk City), Milyutin, L.I., Ed., Novosibirsk: Geo, 2009.

Emlin, E.F., From the settlement until a city: a review of Ural urbanization, in *Ekologiya goroda* (Urban Ecology), Yekaterinburg: Ural. Gos. Univ., 2006, pp. 4–52.

Gosudarstvennyi doklad "O sostoyanii i ob okhrane okruzhayushchei sredy Sverdlovskoi oblasti v 2010 g." (The Governmental Report "On the Status and Protection of Environment in Sverdlovsk Oblast in 2010"), Yekaterinburg, 2011.

Gosudarstvennyi doklad "O sostoyanii i ob okhrane okruzhayushchei sredy Sverdlovskoi oblasti v 2012 g." (The Governmental Report "On the Status and Protection of Environment in Sverdlovsk Oblast in 2012"), Yekaterinburg, 2013.

Harper, K.A., Macdonald, S.E., Burton, P.J., Chen, J.Q., Brosofske, K.D., Saunders, S.C., Euskirchen, E.S., Roberts, D., Jaiteh, M.S., and Esseen, P.A., Edge influence on forest structure and composition in fragmented landscapes, *Conserv. Biol.*, 2005, vol. 19, no. 3, pp. 768–782.

Kolesnikov, B.P., *Lesorastitel'nye usloviya i tipy lesov Sverdlovskoi oblasti* (Forest Conditions and Types in Sverdlovsk Oblast), Sverdlovsk: Ural. Nauch. Tsentr, Akad. Nauk SSSR, 1973.

Konijnendijk, C.C., Ricard, R.M., Kenney, A., and Randrup, T.B., Defining urban forestry—a comparative perspective of North America and Europe, *Urban Forestry Urban Greening*, 2006, vol. 4, nos. 3–4, pp. 93–103.

Laurance, W.F., Ferreira, L.V., Rankin-de Merona, J.M., and Laurance, S.G., Rain forest fragmentation and the dynamics of Amazonian tree communities, *Ecology*, 1998, vol. 79, no. 6, pp. 2032–2040.

Laurance, W.F., Laurance, S.G., Ferreira, L.V., Rankin-de Merona, J.M., Gascon, C., and Lovejoy, T.E., Biomass collapse in Amazonian forest fragments, *Science*, 1997, vol. 278, no. 5340, pp. 1117–1118.

Lebedev, A.V., *Fomitopsis annosa* in recreational spruce forests and diagnostics of tree pathogens, *Izv. Vyssh. Uchebn. Zaved., Lesn. Zh.*, 1998, no. 4, pp. 29–35.

Malmivaara, M., Lofstrom, I., and Vanha-Majamaa, I., Anthropogenic effects on understorey vegetation in *Myrtillus* type urban forests in southern Finland, *Silva Fen.*, 2002, vol. 36, no. 1, pp. 367–381.

Manual on Methodologies and Criteria for Harmonized Sampling, Assessment, Monitoring, and Analysis of the Effects of Air Pollution on Forests, Hamburg: UN Econ. Com. Europe, 1994.

McPherson, E.G., Urban forestry in North America, *Renew. Resour. J.*, 2006, vol. 4, no. 3, pp. 8–12.

Metodika organizatsii i provedeniya rabot po monitoringu lesov evropeiskoi chasti Rossii po programme ICP-Forest (metodika EEK OON) (Planning and Organization of Forest Monitoring in European Part of Russia within the ICP-Forest Program (UN EEC Method)), Moscow: Fed. Sluzhba Lesn. Khoz. Ross., 1995.

Morozov, G.F., *Izbrannye trudy* (Selected Scientific Research Works), Moscow: Lesn. Prom-st, 1970, vol. 1.

Morozova, O.V. and Tarevskaya, N.G., Involvement of alien species of vascular plants in floras of nature reserves of European Russia, *Izv. Ross. Akad. Nauk, Ser.: Geogr.*, 2010, no. 4, pp. 54–62.

Murcia, C., Edge effects in fragmented forests: implications for conservation, *Trends Ecol. Evol.*, 1995, vol. 10, no. 2, pp. 58–62.

OST (State Standard) *56-69-83: The Test Sites for Forestation. Forestation Methods*, Moscow, 1989.

Repshas, E.A., *Optimizatsiya lesopol'zovaniya (na primere Litvy)* (Optimization of Forest Managements in Lithuania), Moscow: Nauka, 1994.

Rysin, L.P. and Rysin, S.L., *Urbolesovedenie* (Urban Forest Science), Moscow: KMK, 2012.

Sanitarnye pravila v lesakh Rossii (Sanitary Rules in Russian Forests), Moscow: Nauka, 1998.

Saunders, D.A., Hobbs, R.J., and Margules, C.R., Biological consequences of ecosystem fragmentation: a review, *Conserv. Biol.*, 1991, vol. 5, no. 1, pp. 18–32.

Selochnik, N.N., Degradation factors of forest ecosystems, *Lesovedenie*, 2008, no. 5, pp. 52–60.

Shergina, O.V. and Mikhailova, T.A., *Sostoyanie drevesnykh rastenii i pochvennogo pokrova parkovykh i lesoparkovykh zon g. Irkutska* (The Status of Trees and Soil Cover in Park and Forest-Park Zones of Irkutsk City), Irkutsk: Inst. Geogr., Sib. Otd., Ross. Akad. Nauk, 2007.

Sturman, V.I., Natural and technogenic factors of atmospheric air pollution in Russian cities, *Vestn. Udmurt. Univ., Biol. Nauki Zemle*, 2008, no. 2, pp. 15–29.

Tolkach, O.V. and Dobrotvorskaya, O.E., The status of reforestation in the green zones of Yekaterinburg, *Izv. Samar. Nauch. Tsentra, Ross. Akad. Nauk*, 2011, vol. 13, no. 1 (4), pp. 919–921.

Weathers, K.C., Cadenasso, M.L., and Pickett, S.T.A., Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere, *Conserv. Biol.*, 2001, vol. 15, no. 6, pp. 1506–1514.

Veselkin, D.V., Koltunov, E.V., and Kaigorodova, S.Yu., The influence of agrochemical properties of soils on distribution of root and trunk rots of Scots pine (*Pinus sylvestris*) in urban forests, *Izv. Samar. Nauch. Tsentra, Ross. Akad. Nauk*, 2013, vol. 15, no. 3, pp. 249–255.

Vidal, C., Lanz, A., Tomppo, E., Schadauer, K., Gschwantner, T., di Cosmo, L., and Robert, N., Establishing forest inventory reference definitions for forest and growing stock: a study towards common reporting, *Silva Fen.*, 2008, vol. 42, no. 2, pp. 247–266.

Zagurnaya, Yu.S., Influence of isolation on composition and species abundance of oak forest phytocenoses in the foothill part of Northwestern Caucasus, *Byull. Mosk. O-va. Ispyt. Prir., Otd. Biol.*, 2008, vol. 113, no. 3, pp. 37–42.

Translated by D. Zabolotny