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Edge Effects on Pine Stands in a Large City

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Abstract—Manifestations of the edge effect on Scots pine (*Pinus sylvestris* L.) trees and stands were evaluated in natural southern taiga forests growing in a large industrial city (Yekaterinburg, Russia). For this purpose, 14 transects were laid out, each consisting of 6–10 circular 400-m^2 plots arranged in a line that extended for 140–260 m into the tree stand, perpendicular to its boundary. During transect surveys, 128 records were made of parameters characterizing the state of pine trees (height, diameter, defoliation level, needle age) and stands (density and timber volume). The boundaries differed in age, i.e., the time of formation (no more than 8 years and more than 20 years ago), and type (adjoining to motorways or wastelands). The edge effect manifested itself only near old boundaries and only for tree height (5 m lower near the boundary than deep in the forest) and for stand density and timber volume (25% lower), independently of the boundary type. Since the test parameters linearly increased with distance from the boundary, it was impossible to estimate the range of the edge effect.

Keywords: ecosystem boundaries, habitat fragmentation, urban forests, urbanization, motorways, *Pinus sylvestris*

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Urbanization is one of the main factors responsible for transformation of natural landscapes, and its significance will further increase with time [1]. A number of studies have been performed to evaluate the impacts of recreational activities and pollution on urban forest ecosystems [2–5]. The consequences of habitat fragmentation for urbanized forests have been less studied and, probably for this reason, their significance is underestimated. Strange as it may seem, studies on fragmentation of urban forests provide almost no data on the state of trees, compared to that under natural conditions [6–10].

Fragmentation enhances edge effects, since it increases the size of ecotonal regions with alterations in the microclimate and the diversity and functioning of the biota [6–10]. Edge effects are regarded as important drivers of ecosystem processes under conditions of fragmentation. For example, carbon emissions due to tropical deforestation have increased by approximately one-third, since about 20% of the remaining area of tropical forests lies within 100 m of a forest edge [11]. Edge effects are highly variable in time and space and manifest themselves differently depending on ecosystem components and their parameters [7, 12, 13]. They are potentially important for the tree layer, including its species composition [14–16], age structure [17, 18], the state of individual trees [19, 20], their mortality, crown closure, biomass, and productivity [7, 12, 13, 21, 22].

Forest fragmentation in cities is often accompanied by the formation of boundaries between forest areas and roads. Changes in the regimes of abiotic factors in the aboveground and belowground spheres are especially contrasting at such boundaries [10, 23, 24]. One more factor making a substantial and probably underestimated contribution to vegetation transformation in urbanized areas is the increased input of nitrogen [25, 26] and its deposition [26, 27], with automobile exhausts being the main source of excess nitrogen in the cities [28, 29]. Therefore, eutrophication is likely to take place at the boundaries of urbanized forests, especially those adjoining roads.

In our previous studies on pine forests in Yekaterinburg, we compared relative significance of their fragmentation and other components of urbanization and obtained evidence for the dependence of the state of tree stand on the size of forest area and the distance of the test plot from the forest boundary, which we attributed to the edge effect [30, 31]. The range of edge effect manifestation with respect to timber volume (70 m) was estimated indirectly, by analyzing the dependence of this parameter on the size of tree stand in a large series of urban and suburban forests [31]. Logically, the next step was to analyze edge effects by direct methods. The results are presented below.

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The purpose of this study was to evaluate manifestations of edge effect in Scots pine (*Pinus sylvestris* L.) trees and stands in forests of natural origin growing in a large industrial city in order to test three hypotheses: (1) the edge effect on trees and tree stands does manifest itself in urban conditions; (2) its manifestations are more distinct at old boundaries, compared to new ones, and at boundaries adjoining roads, compared to those adjoining wasteland; and (3) the extent of edge effect manifestation is 50–100 m. The hypotheses were formulated under the assumption of positive correlation between the state of trees and, on the other hand, the level and/or duration of pollution in a given area and its permeability to the pollutant flow.

MATERIAL AND METHODS

Study region. Yekaterinburg is a large industrial and administrative center in the Middle Urals with a population of 1.5 million, where almost one-third of the total area (15300 ha) is occupied by city forests and forest parks, mostly of natural origin [31]. According to botanical-geographic zoning, the city is in the southern taiga subzone of the boreal forest zone, where prevalent forest types are herbaceous, herbaceous–dwarf shrub, and green moss pine forests with larch [32] on sod-podzolic and brown (burozem) soils. The pollution level in the city is high due to concentration of industries and heavy traffic [28, 29].

Forest massif. Studies were performed in the Yugo-Zapadnyi (Southwestern) forest park located 5–7 km from the city center, where active urban development began 40–50 years ago. The prevailing soils are typical and podzolized burozems, slightly to medium stony, formed under good drainage conditions. They show features typical of transformation under the influence of urbanization: alkalization of upper horizons by 0.2–0.5 pH units (in suburban forests, pH_{water} is 5.0–5.5 in the litter and 5.4–5.7 in the humus horizon), increased calcium content in the exchangeable complex, and enrichment with mobile nitrogen [27]. The forest park currently consists of four forest areas 40–150 ha in size that are spatially separated from each other by roads or wastelands to distances of 100–200 m.

Experimental scheme. Criteria for the placement of test plots were as follows: (1) tree stand of natural origin; (2) proportion of pine in growing stock no less than 70%; (3) average tree age no less than 100 years; (4) location in transitional topographic positions with site conditions corresponding to the herbaceous group of forest types; (5) the absence of fresh, large-scale, and/or purposeful disturbances to the soil cover (roads, excavations) and tree stand (fires, tree cutting).

To analyze edge effects, test plots were arranged in lines (transects) that extended into the tree stands perpendicular to their boundaries. The term "boundary" in this context refers to the separation line between a continuous forest massif and the adjacent treeless area (a road or wasteland). A transect consisted of ten circular test plots (in some cases, six to nine plots) with a radius of 11.28 m (400 m^2 in area), each with a pine tree in the center, located at intervals of 23–30 m. The first plot, semicircular in shape, was established directly at the boundary of a given stand. The transects were divided into groups depending on the time of formation (age) and type of the boundary (Table 1). Boundaries formed no more than 8 years ago were classified as new, and those formed no less than 20 years ago, as old. With respect to the type of the boundary, we distinguished between transects adjacent to roads with heavy traffic and to unbuilt areas without roads (referred to as wastelands). The first plots of the transects were located 5.2–6.7 km from the city center and 0.2–1.2 km from the nearest built-up residential areas. A total of 14 transects with 128 plots were established.

Assessment of the state of trees and stands. All pine trees in each plot were counted, measuring trunk diameter at breast height (DBH) with a caliper to an accuracy of 1 cm and tree height with an electronic hypsometer to an accuracy of 0.5 m. Only trees with a DBH of more than 8 cm were included in analysis. The volume of standing timber in the plot was calculated by summing the products of multiplying the trunk cross-section area at breast height by form height (the parameter depending on tree species and the top height of the stand) [33]. In the first semicircular plots (200 m^2 in area), the recorded number of trees (except the central tree) was multiplied by two in order to normalize the results relative to those in other 400-m^2 plots. Each tree was examined with binoculars to estimate the level of defoliation with a 5% accuracy [34] and the average age (to the nearest half-year) of needles on three to five branches [35].

Statistical analysis. The strength of edge effect on the test parameters was estimated from the pattern of parameter dependence on the distance from stand boundary. We used linear mixed models (*LMM*) with random effect where the distance from the boundary, boundary type (road or wasteland), and boundary age (new or old) were fixed factors, and transect number was random factor. This approach allowed us to take into account individual differences between the transects. The dependence of parameters on the distance from a given variant of the boundary was analyzed using linear models (*LM*) with random effect (transect number). The false discovery rate (*FDR*) in multiple comparisons of statistical hypotheses was controlled using the Benjamini–Yekutieli adjustment (below, all *P* values of significance are *FDR*-corrected). Different models of parameter–distance relationships (linear, polynomial, and logistic) were compared using the Akaike information criterion (*AICc*). Calculations were made with JMP 10.0.0 software (SAS Institute Inc., United States, 2012).

Table 1. Characteristics of transects

No.	Coordinates of the first plot		Boundary		Number of plots	Distance from the last plot to the boundary, m
	latitude N	longitude E	type	age (time after cutting), years		
1	56°47′33.20″	60°35′36.60″	Road	3	7	173
2	56°47′25.80″	60°35′37.90″	″	3	9	168
3	56°47′9.70″	60°35′48.90″	″	3	10	268
5	56°47′37.00″	60°33′22.00″	Wasteland	7	9	200
6	56°47′33.70″	60°33′22.10″	″	7	10	146
7	56°47′31.60″	60°33′44.30″	″	>20	10	232
8	56°47′30.60″	60°34′5.30″	″	>20	10	160
9	56°47′16.70″	60°34′4.60″	Road	>30	10	245
10	56°47′10.90″	60°34′0.00″	″	7	10	225
11	56°47′0.20″	60°33′45.50″	″	>30	10	141
12	56°47′7.40″	60°33′57.60″	″	7	7	150
13	56°47′55.10″	60°31′58.70″	″	7	10	225
14	56°46′58.10″	60°35′51.50″	″	>40	6	90
15	56°47′22.40″	60°34′40.50″	″	>40	10	230

Table 2. Significance levels (*FDR*-corrected *P* values) of the effects of factors on the state of pine trees and stands in linear mixed models with random effect (transect number)

Parameter	Source of variation						R^2_{adj}	
	distance [1]	boundary age [2]	boundary type [3]	[1] × [2]	[1] × [3]	[2] × [3]	*M*1	*M*2
Morphometric parameters of trees								
Average diameter	1.0000	0.5439	1.0000	**0.0364**	1.0000	1.0000	0.29	0.10
Average height	0.1000	0.7743	1.0000	**0.0001**	0.8747	1.0000	0.47	0.24
Parameters characterizing life state of trees								
Defoliation level	0.1786	0.8245	1.0000	1.0000	1.0000	1.0000	0.30	0.02
Needle age	1.0000	0.4636	1.0000	1.0000	0.3058	1.0000	0.31	0.12
Parameters of stand								
Density	1.0000	0.7526	1.0000	**0.0154**	1.0000	0.7387	0.24	0.14
Timber volume	1.0000	0.4474	1.0000	**0.0451**	0.6306	0.6586	0.30	0.20

(R^2_{adj}) determination coefficient R^2 adjusted for the number of parameters, (*M*1) complete model, (*M*2) model without random effect. Boldface indicates that $P < 0.05$.

RESULTS

Strength of edge effect. Complete models with fixed and random factors explained 24–47% of the variance (Table 2), but most of it was associated not with the edge effect itself but rather with differences between the transects (33–93% of the variance explained by the complete model). The type and age of the boundary themselves, either separately or in interaction, were not found to have any effect on tree stand, indicating relative uniformity of the studied forest areas.

No edge effect was revealed when all the transects were considered together. However, a significant role of the interaction of factors (the distance of the plot from the boundary and the age of the latter) was indicative of the edge effect manifested in different directions near new and old boundaries, independently of their type.

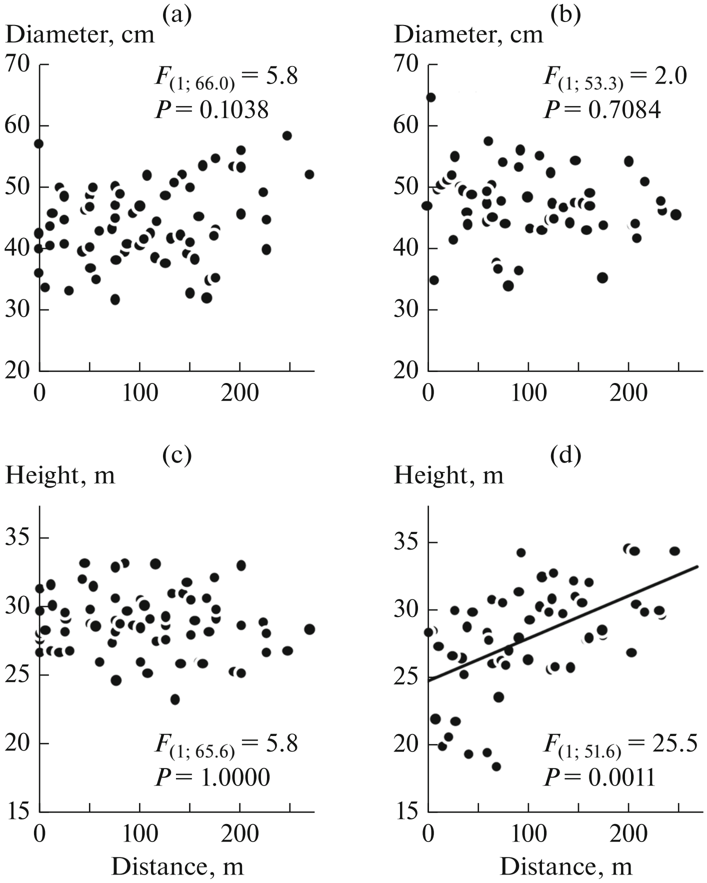

Fig. 1. Dependence of (a, b) average diameter and (c, d) average height of pine trees on the distance from stand boundary for (a, c) new and (b, d) old boundaries ($n = 72$ and $n = 56$, respectively). Here and in Fig. 2, Fisher's F and *FDR*-corrected P values for linear models with random effect (transect number) are given. Linear approximations are shown only for statistically significant effects ($P < 0.05$).

The edge effect was also unequally manifested in different parameters: it was confirmed for morphometric characteristics (diameter and height) and parameters of tree stand (density and timber volume). but not for the life state of trees. The average tree diameter showed no significant changes with distance from the boundaries, either new (Fig. 1a) or old (Fig. 1b). The same was true of average tree height on transects from new boundaries (Fig. 1c), but in the case of old boundaries (Fig.1d) this parameter was approximately 5 m lower in peripheral plots located at no more than 40 m from the boundary than in central plots located farther than 120 m from it ($m \pm SE$: 24.8 ± 1.0 m, $n = 13$ vs. 29.8 ± 0.6, $n = 22$). The edge effect on stand density and timber volume was also significant only in the transects from old boundaries (Fig. 2): both parameters were 25% lower in peripheral than in central plots (9.8 ± 1.2 vs. 13.1 ± 0.9 trees/400 м^2 and 18.6 ± 8.7 vs. 24.7 ± 6.8 m^3/400 m^2).

For parameters showing regular changes near old boundaries (Figs. 1d, 2b, 2d), the edge effect itself contributed about one-half to the proportion of variance explained by a complete model (27–54%): the determination coefficient for tree height is $R^2_{\text{adj}} = 0.54$ in the complete model versus $R^2_{\text{adj}} = 0.28$ in the model without random effect; for stand density, $R^2_{\text{adj}} = 0.27$ vs. $R^2_{\text{adj}} = 0.14$; and for timber stock, $R^2_{\text{adj}} = 0.27$ vs. $R^2_{\text{adj}} = 0.15$, respectively.

Range of edge effect. To estimate a threshold in the manifestation of edge effect, we analyzed the form of dependence between parameters for which this effect was reliably conformed and the distance from the stand boundary and compared the quality of linear and nonlinear approximations (Table 3). The results provided no evidence for nonlinearity of change in any parameter depending on distance: in all cases, the minimum *AICc* values were obtained for linear approximation, with its quality exceeding that of polynomial and logistic approximations by factors of 1.5–3 and 1.5–10, respectively (according to the ratio of Akaike weights). Thus, the average tree height, stand density, and timber volume monotonically increase over a distance of 200–250 m

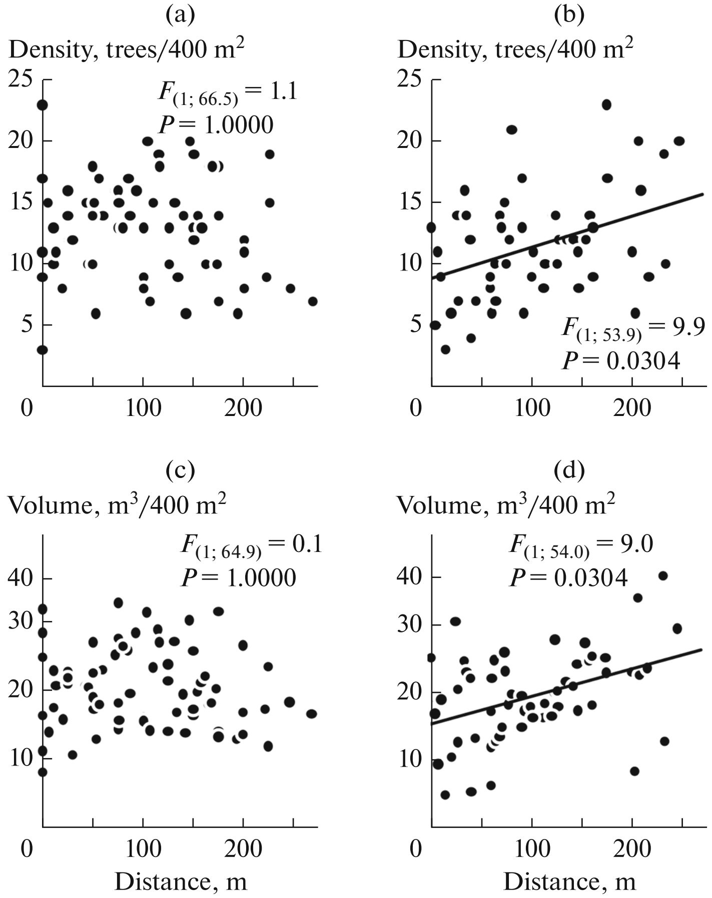

Fig. 2. Dependence of (a, b) pine stand density and (c, d) timber volume on the distance from stand boundary for (a, c) new and (b, d) old boundaries ($n = 72$ and $n = 56$, respectively).

from the boundary toward the center of tree stand, without any stabilization.

DISCUSSION

The data presented above provide evidence that the edge effect on pine trees and stands manifests itself in city forests of Yekaterinburg. On the one hand, this result is expectable and, hence, somewhat trivial; on the other hand, we are not aware of any publications dealing with the assessment of edge effects on forest-forming species in urban forests. Numerous studies on forest fragmentation under urbanization involved analysis of various objects, e.g., animals and fungi [36, 37], herbaceous plants and shrubs [3, 38], but not trees.

Our first hypothesis is confirmed only partially, because the edge effect has not been observed for all the test parameters. It can be reliably concluded that the average tree height, stand density, and timber stock increase from the periphery toward the center of tree stand. The basis for discussing the edge effect on the average diameter of trees and parameters of their life

Table 3. Values of (*AICc*) Akaike information criterion and (*w*) Akaike weight for different models describing the dependence of tree and stand parameters on distance from stand boundary for transects with old boundaries ($n = 56$)

Parameter	Model					
	linear		second-degree polynomial		four-parameter logistic	
	AICc	*w*	*AICc*	*w*	*AICc*	*w*
Average tree height	296.3	0.495	298.2	0.194	297.2	0.310
Stand density	320.6	0.701	322.8	0.230	325.2	0.070
Timber volume	376.4	0.675	378.4	0.246	380.6	0.080

state is much weaker. The edge effect in this case is adverse, in agreement with ample evidence for degradation of trees at the boundaries of natural forests [8, 17, 21, 39]. However, opposite examples are also known [16, 19, 40], and it is therefore emphasized in review articles that the consequences of this effect are ambiguous [7, 12, 13]. The observed direction of transformation in the state of trees and tree stand at the boundaries of forest areas coincides with the results of our previous study [31]. It appears that depression in tree height at the edges of stands is explained by relatively low competition for light, and decrease in stand density, by higher die-off rate under the impact of pollutants and winds [6, 9, 10, 24].

The second hypothesis is also confirmed only partially: the degree of manifestation of the edge effect depends on the age of boundaries (old or new) but not on their type (road or wasteland). Transformation in the state of trees and stands has taken place only near the boundaries existing for a long time, representing a cumulative response to changes in environmental conditions. The dependence of manifestation of the edge effect on the time period after fragmentation shows that tree stand degradation in the marginal zone is a delayed process. This phenomenon, similar to the delayed extinction of species after habitat fragmentation [41], is due to the high inertia of supraorganismal systems. Effects related to such a delay are least studied but important for understanding the phenomenon of fragmentation [13].

It is noteworthy that, despite a considerable period of existence of old boundaries (20–40 years), the recorded responses of trees at the edges of stands can hardly be considered strong: the difference in tree height between the outermost and innermost plots is about 15%, and differences in stand density and timber volume, 25%. Such small differences agree with data on insignificant changes in the state of trees at the edges of stands [17, 19], on the absence of significant negative consequences of edge effects for carbon deposition [16, 40], and, in general, on high variability and multidirectionality of edge effects on the vegetation [7, 13].

The small amplitude of edge effects and the absence of their manifestation in parameters of life state are evidence for low sensitivity of mature pine trees to changes in conditions at the boundaries of urbanized forests, which agrees with our conclusion that mature trees of this species are relatively tolerant to the impact of urbanization [30]. Such a small amplitude may be accounted for by the age of pine in city forests of Yekaterinburg: trees of the main generation in the test plots are 110 to 140–160 years old [30]. Therefore, when old boundaries were formed (20–40 years ago), they were more than 70 years old, and pine stands of this age are usually past of the stage of peak increments and strong thinning [42].

We initially supposed that edge effects of equal amplitude could result either from long-term accumulation of small disturbances under low-contrast conditions at the boundary or from relatively rapid changes in the state of trees under high-contrast conditions. Therefore, it was expected that edge effects would be especially strong near motorways, which can have a significant influence on trees [20, 23], but no difference between the boundaries near roads and wastelands was revealed. This could be due to an unbalanced experimental scheme (only 4 out of 14 transects adjoined wastelands) as well as to other causes, which require additional analysis.

The third hypothesis was based on the assumption that depression in tree height or timber volume manifests itself only to a certain distance from the boundary, with subsequent stabilization of the corresponding parameter. Based on available estimates [7–10, 31, 39], we expected to find that stability of the stand in its inner parts is provided for by its marginal zone about 50–100 m in width. However, no evidence was obtained for nonlinearity of edge effects over a distance of 200–250 m, and, hence, any discussion about a certain threshold distance would be groundless. This fact contradicts our previous estimation concerning a 70-m range of manifestation of edge effect in pine forests of Yekaterinburg [31]. This estimation was made by comparing the state of different types of stands—small forest fragments remaining within built-up residential areas, city forests, and suburban forests—without distinguishing between the edge effect itself and the effect from decreasing size of forest fragments. Here, only the edge effect is considered, because the areas of forest massifs included in the study do not significantly differ from each other. The absence of a threshold in the edge effect indicates that, in urbanized forests, a 200-m zone is insufficient for reliably approximating the dependence of test parameters on the distance to the boundary. However, it cannot be excluded that an important role is also played by another consequence of forest fragmentation, namely, the decrease in the size of resulting fragments.

Thus, the edge effect is a significant but not at all the main factor determining the state of southern taiga forests in a large industrial city. Tree height, stand density, and timber volume in such forests are consistently lower in zones adjoining their boundaries, but no change in the life state of trees has been revealed in these zones. The main factor modifying manifestations of edge effects is the age of the boundary (i.e., the time elapsed after fragmentation): these effects manifest themselves only near old boundaries (20–40 years) and are probably enhanced with time. It is necessary to analyze in more detail the question concerning the delayed degradation of tree stands in marginal zones in order to more reliably predict the directions and rates of forest transformation because of fragmentation. Further studies should also include the search for determinants of the state of tree stand, since a considerable part of its variation is related to differences between local zones (transects) and has not yet been explained.

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