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Edge Effect: Growth and Morphogenetic Features of Scots Pine Trees in Forest Parks and Natural Stands

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Abstract—The degree of development and depth of edge effect are studied in some fragments of forest-park stands under long-term urbanization impact (in the city of Yekaterinburg, Russia) and in natural forests using the method of transect investigation. The method of quantitative assessment of tree stem and crown growth features by a set of morphological characteristics was used. The objects of the research included the edges of Scots pine stands. The edge effect was determined by two of the five studied characteristics: foliation and branchiness, which characterize the level of the development of the tree assimilation apparatus. The general trends indicate an increase in the development of these characters in natural stands and decrease in the forest park at increased distance from the edge. The nonlinear development of morphological characteristics along the transects is due to different types of tree responses on the impact of determining morphogenesis factors. Four statistically significant different zones were identified in the natural stands at distances of 0–75, 100–125, 150–175, and 200–225 m from the forest edge and only two zones were differentiated in the forest park. The unified approach to data analysis suggests the edge effect in both habitats at a distance of 75–100 m from the forest edge according to branchiness and 100–125 m according to foliation. Several types of morphogenetic tree responses, distinguished by the degree of foliation and branchiness variation under edge effect impact, are revealed.

Keywords: edge effect, pine stand, tree growth and morphogenesis, visual assessment scales, *Pinus sylvestris* L., spatial dynamics

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Urbanization of forested areas increases forest fragmentation. This makes it highly relevant to study the influence of edge effects on the state of forest ecosystems and their biological diversity under different urban and suburban impact [1–5]. The main contributing factors of fragmentation include changes in the combination of microclimatic environmental conditions [6], as well as the influence of a set of biotic factors (intra- and interspecific competition and changes in the composition of plant communities and other biota components and in soil properties) [7]. It is known that primary changes at the edge of stands causes long-term responses of the biotic community and their development deep into the forest. According to different estimates, the depth of the edge effect is 20–100 m for forest stands [5, 8–11], about 30 m for the grass–dwarf-shrub layer [12] and can reach 300 m in tropical forests, depending on their specific characteristics [13].

A previous study of suburban forest park and urban pine stands revealed an increase in the tree viability index (needle density and needle lifetime) deep in the forest stand [11]. These changes are accompanied by a transformation of the morphological structure of the stand; in particular the density [14] and relative height of trees decrease at the forest edge, indicating their light demand [1, 8, 15, 16]; at the same time, the edge effect is less pronounced in elder stands [17].

The study of the edge effect in young and elder forest edges using the transect survey method showed that the height, diameter, viability, density and stem volume of pine stands linearly increase with distance from the forest edge [18]. At the same time, nonlinear relationships were not found within 250 m: the edge effect was statistically significant along transects at old edges, while it was absent along recent ones. Since the development of the edge effect deep into a forest stand covers tens of years [6], the processes accompanying this phenomenon are connected with adaption to the effect of all external factors. The adaptive pattern of responses at the level of separate trees and the entire forest allows us to suggest that one of the developments of edge effect may be the implementation of the morphogenetic adaptation potential in the form of accumulation of separate morphological characters during ontogenesis.

Based on the example of pine stands, it was previously shown [19] that the quantitative approach to assessing separate characteristics of the stem and crown shape, which reflect the integral responses of trees to the influence of external factors, is effective and perspective for the study of tree growth and development. Therefore, two working hypotheses were put forward while planning this study. The first hypothesis is that a set of adaptive tree responses (expressed in their growth and morphogenetic changes) is observed in the gradients determining the edge effect of environmental conditions. Some of these morphometric features are informative, since they naturally vary with respect to the distance to the forest edge. The second hypothesis is that the spatial dynamics of the values of the characteristics differs in natural stands and forest parks.

The main objective of this research was to reveal the morphometric characteristics of Scots pine (*Pinus sylvestris* L.) in the edge effect zone, which are informative for studying spatial dynamics, and to determine (based on a comparative analysis of their values) the degree of development and depth of the edge effect in long-term existing fragments of natural stands and a forest park in a large industrial center (the city of Yekaterinburg).

The following tasks were set for testing these hypotheses:

(1) To measure a set of growth and morphogenetic characteristics of trees on a representative number of transects with sufficient lengths to register the edge effect in the natural stands and forest park.

(2) To analyze the data and reveal the characters that are sensitive to the edge effect (informative characters) by determining the presence and pattern of the relationship of the values of these characters with the distance to the forest edge, as well as the effect of the forest edge on the variation in separate characteristics.

(3) To establish and compare the boundaries of the zones with different patterns of development of the edge effect in the studied stands based on the analysis of the dependences of the informative characters on the distance to the forest edge, combined with cluster analysis.

MATERIAL AND METHODS

The studies were carried out in 2015–2017 in the forest park and natural pine stands. The forest growth conditions and characteristics of anthropogenic factors influencing the state of the stands in the city of Yekaterinburg are the same as those previously described in [11]. The study areas are located in the Trans-Ural foothill province of the South Taiga district [20]. The area of the city is exposed to airborne industrial pollution (mainly vehicle emissions); as a result, the soils have accumulated a significant amount of heavy metals [21–23].

The presence and depth of the edge effect were assessed by the transect survey method. The conditions for selecting plots were previously described in [18]. Ten sampling plots with a radius of 11.3 m were laid on each transect; they were established deep from the forest edge at a distance of 25 m between their centers. Transects were created at the edges of stands that appeared over 20 years ago in the Yugo-Zapadnyi (Southwestern) forest park and at a distance of 10 to 30 km to the south and west of the city (near the localities of Aramil, Bobrovsky, Dvurechensk, Kashino, and Khrustalny). In total, six transects were investigated in the forest park and ten transects in the natural stands (nos. 7–9, 11, 14, and 15 and 16–19, 23–25, and 28–30, respectively). Among them, transects nos. 14 and 18 were shortened (six sampling plots). Trees with a diameter of not less than 8 cm were completely considered in each plot. A total of 2315 trees growing in 152 plots were studied.

During the study of the edge effect, the diagnostic features of trees were determined using the method of quantitative assessment of the degree of growth changes related to the morphogenetic adaptation [19]. The test characteristics of the stem and crown of a tree (multiple stems, multiple tops, stem curvature, branchiness, and foliation) appeared and changed during its ontogenesis. The stem curvature is determined by the number of bends with a deflection arrow of not less than 0.5 of the diameter; branchiness is determined by the number and branchiness of living and dead branches that have been left on the entire stem; and foliation characterizes the number, degree of density, and distribution of needles in the crown. Therefore, the latter two characters describe the degree of development of the tree assimilation apparatus. It should be noted that all these characteristics are measured discretely in time and their values are determined using point grading scales.

The data were statistically analyzed using a standard software package, Statistica 8.0 (StatSoft Inc., 2007). We used methods of regression and cluster analysis, as well as a nonparametric analogue of one-way ANOVA. The cluster analysis was based on the Euclidean metric and Ward's method. The spatial dynamics of the parameters with distance from the forest edge was visually represented by calculating a standard error and 95% confidence interval for the mean value in the respective plots. Since the values of branchiness and foliation were initially measured in grades and their distributions were significantly asymmetrical (standardized asymmetry from –2.6 to –10.4), they were analyzed using medians as a central trend and the resulting central trends were compared using the Kruskal–Wallis rank test.

RESULTS

Analysis of the results shows that the stands are dominated by single-stem trees on all transects, while

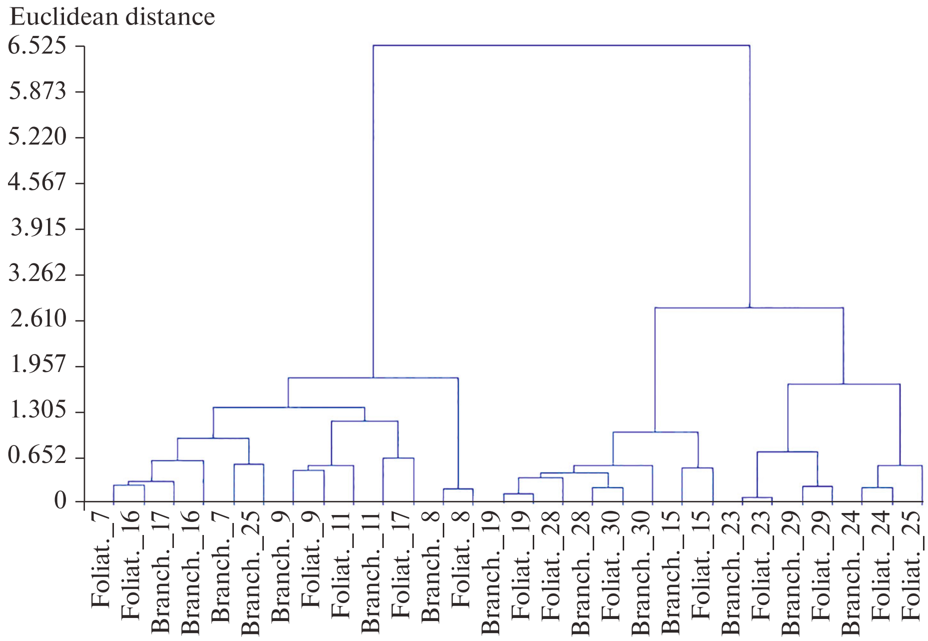

Fig. 1. Clustering of the spatial dynamics of the branchiness and foliation values on transects: Branch. and Foliat. – branchiness and foliation; (7)–(30) – transect numbers.

the edge effect is not determined by the multiple stem character. On the average, multiple tops and the degree of stem curvature are higher in the forest park than in the suburban area ($H_{(1; 2315)} = 24.88$; $p < 0.001$ and $H_{(1; 2315)} = 12.89$; $p < 0.001$, respectively); however, the dependence of the values of these characters on the distance, as well as the effect of the distance factor on their variation, were not found in the edge effect zone. Therefore, no developments of the edge effect were revealed for these characters. It should be noted that the values of branchiness and foliation are higher in natural stands than in the forest park ($H_{(1; 2315)} = 42.85$; $p < 0.001$ and $H_{(1; 2315)} = 68.25$; $p < 0.001$, respectively) and change with distance from the forest edge, as shown below.

Therefore, a cluster analysis of the spatial dynamics of the branchiness and foliation values along the transects was carried out at the first stage of studying the edge effect in the natural stands and forest park. The average values in each transect site served as analytic characters and changes in the characters with respect to the distance to the forest edge served as objects. Since the values of these characteristics are approximately in the same range (about 3 grades), these two parameters were separately considered during the calculation of the distances between spatial changes in the characters. Clustering makes it possible to differentiate two main groups, the composition of which corresponds to the division of the transects into forest-park and suburban transects with a few exceptions (Fig. 1). Analysis of all transects, including the shortened ones (nos. 14 and 18), in the six plots confirms this pattern. It should be noted that the clustering of all trees in both habitats according to the above-mentioned characters differentiates four general clusters (the results are not shown here due to the large array of data and complexity of their representation). Two of these clusters combine trees with the highest and lowest values of the parameters, respectively, and the other two include trees with the intermediate values.

The established differences between the transects in the forest park and natural stands indicate that it is reasonable to separately study the edge effect for these habitats. Therefore, we then independently compared the averaged values of the characters for these objects.

The comparison of natural stands and forest parks shows that they differ in linear trends of branchiness and foliation values along the transects (Figs. 2, 3): according to these characters, the trends are weak and positive for the natural stands, while they are negative for the forest park. The values of the characteristics were averaged during analysis of the dependence of the characters on the distance to the forest edge. To visually represent the form of dependence of the characters on the distance, we added polynomial trends of the 6th order (Figs. 2 and 3), in which all coefficients are significant ($p < 0.05$), unlike the polynomials of other orders. According to the obtained data, the level of foliation and branchiness significantly decreases at a distance of 25 m from the forest edge. A relative stabilization of these parameters begins to be observed in the forest park with distance from the forest edge (see Fig. 3). In natural stands, the values of both characters successively increase and decrease (see Fig. 2); the

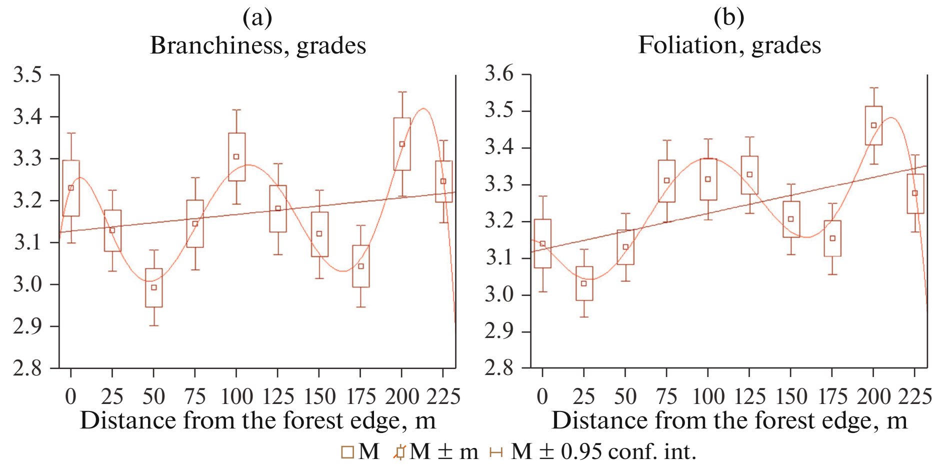

Fig. 2. Linear, polynomial trends and averaged values of (a) branchiness and (b) foliation at different distances from the edge in natural stands.

values and position of the extrema in the regression curves significantly differ from the corresponding characteristics in the forest park. The complex form of the obtained correlations makes it difficult to determine the depth of the edge effect. To establish its depth, we divided the data from all transects into groups, each of which combined the results of measurements at adjacent sites. The inclusion of a tree to a certain group corresponding to the range of distances from the forest edge was considered as a factor influencing the branchiness and foliation of this tree.

A complete analysis of the entire combinatorial set of spatial zones for the number of groups from 6 to 2 and number of grouped plots from 2 to 5 revealed four zones that are statistically significantly different in both characters for the transects in the natural stands (see Table 1); the centers of the plots in these zones were located at distances of 0–75, 100–125, 150–175, and 200–225 m from the forest edge.

The same analysis revealed only two statistically significant different groups of plots in the forest park. At the same time, the location of the boundary between them is at a distance of 75–100 m from the forest edge according to the branchiness character ($H_{(1;554)} = 6.56$; $p = 0.010$) and 100–125 m according to the foliation character ($H_{(1;554)} = 8.33$; $p = 0.004$). Below, the values of these distances are considered as assessments of the depth of the edge effect according to each of the characters.

To compare the data results for the transects in the forest park and natural stands, we additionally analyzed the latter by combining the plots into two groups, followed by the choice of the variant with the best parameters of statistical significance. This made it possible to establish the following edge effect boundaries: at a distance of 75–100 m according to branchiness ($H_{(1;1761)} = 6.84$; $p = 0.009$) and 100–125 m according to foliation ($H_{(1;554)} = 8.33$; $p = 0.004$). These values correspond to the localization of the edge effect boundaries in the forest park; however, it should be noted that the best parameters for the transects in the natural stands are significantly lower (by several times) during the differentiation of two zones than their respective parameters during the differentiation of four zones.

Analysis of the relationship of the frequencies of tree occurrence with the maximum or minimum values of the two characters sensitive to the edge effect (Fig. 4) shows that the shapes of the curves of the dependence of the natural stands on distance to the forest edge are characterized by the alternation of oppositely directed extrema. Individuals with the minimum values of the characters prevail here. A similar pattern of frequency

Table 1. Assessment of the significance of the distance from the forest edge impact on the foliation and branchiness values in the four zones differentiated in natural stands

Zone no.	Distance to the center of the plot, m	Foliation		Branchiness	
		Average rank	H-statistics; *p*-level	Average rank	H-statistics; *p*-level
1	0–75	825.87	32.80; <0.001	845.51	22.63; <0.001
2	100–125	959.85		942.94	
3	150–175	838.05		823.45	
4	200–225	978.25		964.98	

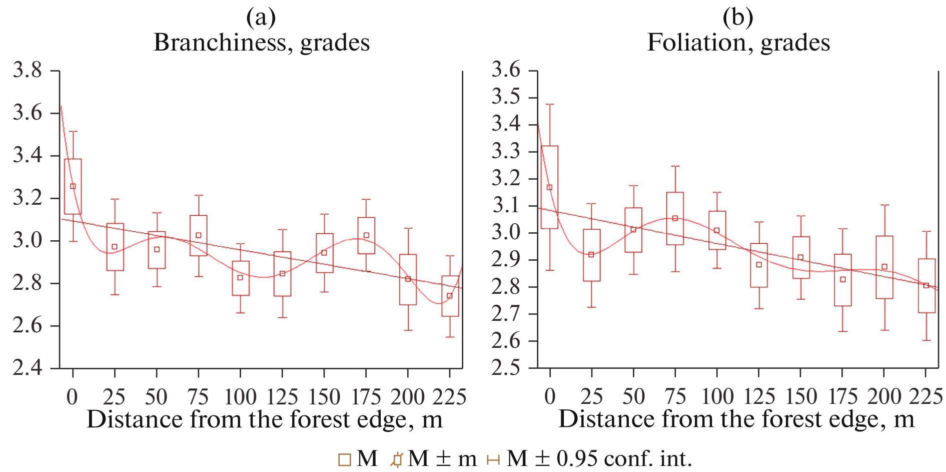

Fig. 3. Linear, polynomial trends and averaged values of (a) branchiness and (b) foliation at different distances from the edge in the forest park.

changes is observed in the forest park; however, their spatial dynamics significantly differs: the extrema are less pronounced and individuals with the maximum developments of the characters prevail.

DISCUSSION

The main factor of multiple stem and multiple top formation in pine is mechanical or entomological damage of its apex shoot at young and mature ages, leading to the further formation of several stems or tops. The absence of differences between stands in different habitats by the first character, as well as the significant increase in the number of multiple tops in the forest park, indicate a growth in the effect of this factor over time under urban environmental impact. The causes of the formation of pine stem curvature have not yet been revealed, except obvious responses to external effects (mechanical damages and gravi- and phototropisms). Additional studies are required to explain the mechanisms of this phenomenon and growth of its developments under urban impact.

The absence of the influence of the edge effect on three of the five measured characters is explained by the independence of their formation and indicates that they are insensitive to the effect of forest-edge environmental conditions [5]. Branchiness and foliation are integral indicators and characterize the general development of the assimilation apparatus. Their higher values in natural stands than in the forest park, as well as the difference in their spatial dynamics on the transects in the natural stands and in the forest park (see Fig. 1), indicate the response of processes that determine the formation of these characters in the edge effect zone. The opposite pattern of their linear trends with distance from the forest edge (see Figs. 2 and 3) is explained by the influence of urbanization on the state of the tree assimilation apparatus. The set of the above-mentioned facts confirms the first hypothesis and, in part, the second one.

The shape of the trend curves approximating these relationships of branchiness and foliation with distance indicates a significant nonlinearity of their development along the transects, which is presumably determined by the superimposition of the effects of environmental factors on the test characteristics of tree responses. Thus, the reduction of the parameters at a distance up to 25 m from the forest edge is explained by an obvious change in illumination [8] and temperature conditions [1, 6]. This effect is more significant in the forest park than in natural stands, which suggests currently undetermined additional factors forming the regional effect in the urban zone. It should be noted that the structure of pine trees changes in the forest park near the forest edge: according to the calculations of the relative morphological parameters of pine trees, their relative height decreases here [16].

The results of one-way ANOVA of the dependence of foliation and branchiness on distance to the forest edge suggest the structured (four different zones) and possibly spatially extensive (over a distance of about 200 m) influence of the edge effect on the spatial dynamics of these pine indicators on suburban transects. The differences in the number and localization of the boundaries between the zones according to these characters for the natural stands and forest park (the latter includes only two differentiated zones) additionally indicate the change in the state of the growth processes of trees in the city. When the number of zones in natural stands was reduced to two during data analysis (for comparing the results with the forest park data), the positions of the boundaries between them coincided. If we assume that the distance from the forest edge to the boundary between the first and second zones is equal to the depth of the edge effect, it is 25 m larger for foliation than for branchiness, which

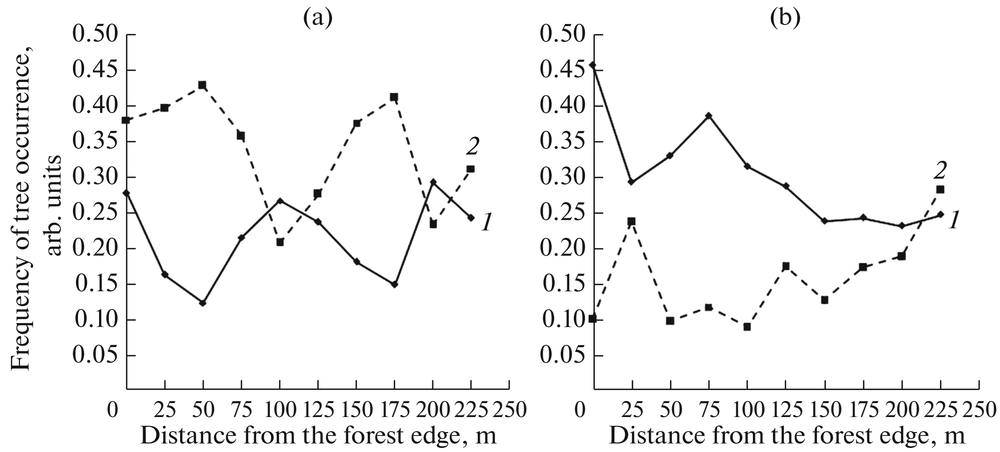

Fig. 4. Spatial dynamics of the frequencies of tree occurrence in groups clustered according to the set of (*1*) maximum or (*2*) minimum values of branchiness and foliation: (a) suburban group, (b) forest park.

apparently reflects a higher sensitivity of this character to environmental factors. It should be noted that the results of analysis of the data on the values of four of the five studied characters (with the exception of multiple stem), as well as on the spatial dynamics of foliation and branchiness in the studied habitats, confirm the validity of the second hypothesis.

The presence of the four clusters that were differentiated during the analysis of all (regardless of the location) studied values of tree branchiness and foliation (groups with maximum and minimum values and two groups with intermediate values) suggests four different types of pine tree responses in the edge effect zone to the set of factors determining morphogenesis. In addition, our research revealed a significant difference in the spatial dynamics of the occurrence of trees with contrasting types of morphogenetic responses in the natural stands and forest park. It should be noted that the revealed patterns and assumption of the existence of types of adaptive morphogenetic responses are based on the results of analysis of the values of the features of the assimilation apparatus development and are consistent with the existence of different tree growth strategies according to Kraft's classification.

CONCLUSIONS

(1) The research of morphogenetic features of pine trees has revealed that natural stands and forest parks do not differ with respect to their multiple stem parameter. Stem curvature and multiple peaks are significantly more often registered in the forest park; however, there is no edge effect according to these characters.

(2) The edge effect is observed according to foliation and branchiness; the linear trends of their changes show an increase in these characteristics for natural stands and their decrease for the forest park with distance from the forest edge. The spatial dynamics of the values of these characters are also different.

(3) The nonlinearity of the development of branchiness and foliation along the transects indicates the complex nature of processes determining the formation of the edge effect in the forest stand. One of the causes of the nonlinearity of the established dependences is the presence of four types of tree responses to the set of factors determining morphogenesis both in natural stands and in the forest park. The formation of the edge effect presumably depends on their combination.

(4) One-way ANOVA of the dependence of branchiness and foliation values on distance to the forest edge makes it possible to differentiate four statistically significant different effects on the variation in the values of these characters on transects in natural stands. The centers of the plots included in the zones are located at distances of 0–75, 100–125, 150–175, and 200–225 m from the forest edge. The presence of several zones indicates the complex nature of the edge effect in natural stands. Only two zones differ in a statistically significant way in the forest park, which is probably due to changes in the number and/or contribution of the influencing factors.

(5) The unified approach to determining the boundary of the edge effect, including the differentiation of two zones, makes it possible to compare the conventional depth of the effect in the two habitats. In the natural forest stands and forest park, the edge effect is observed at a distance of 75–100 m according to branchiness and 100–125 m according to foliation. The difference in the depth of the edge effect according to these characteristics is about 25 m and is probably explained by the features of adaptive morphogenetic responses of trees. The total depth of the edge effect, considering both variants of zonation for each character, is about 125 m in the forest park and 175 m in natural stands. The edge effect is most unidirectional with respect to foliation and branchiness at a distance of up to 25 m from the forest edge.

(6) Several types of morphogenetic tree responses, distinguished by the degree of foliation and branching changes due to the edge effect, were revealed.

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