Assessment of the influence of various tree species and their parameters on the behaviour of wind flows in urban environments (on the example of the RUDN University campus, Moscow)

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Abstract. Urban environments are constantly growing, as a result of which natural surface covers are replaced by artificial materials. These changes have a strong impact on the wind fields in these urban environments, changing speeds and directions of wind flows. The aim of this study is to assess the effects of various tree parameters on the behaviour of wind flows in an urban environment. The EnviMet software package is used to model wind fields. The study is conducted in the city of Moscow on the RUDN University campus. Ten different kinds of trees are identified with characteristics such as tree height, crown width, trunk height, and the LAD (Leaf Area Density) index. For these species, a similar analysis is carried out to assess their impact on the wind field. The height of the trunk has a significant effect on the wind field at the pedestrian level; depending on the parameter, the wind speed and the area of wind gusts increase. Large crowns create a protective barrier, reducing wind activity. At the same time, a high LAD index creates low wind permeability, as a result of which the wind flows are refracted, and dangerous zones arise. On the other hand, a high LAD index reduces the area of wind gusts.

1. Introduction
The study of the behavior of wind flows in an urban environment is gaining popularity and is an urgent problem of urban climatology. Wind flows have a diverse effect on the urban climate: the distribution of pollutants [1-4], pedestrian comfort [5-9], the assessment of wind risks [10-14]. Recently, this problem is relevant, and many scientists are studying the behavior of wind in the city using micro-scale models [15-17]. For Moscow region, modeling studies were performed previously for thermal fields [18-21] as well as for thermal comfort conditions [22].
The urban structure significantly affects the behavior of wind flows. Buildings, trees, and other obstacles change the direction and speed of the wind, contributing to the formation of zones with reduced aeration [23-26] or, vice versa, leading to an acceleration of wind speed, up to dangerous values that can lead to destruction [27-31].

Most scientists are solely focused on studying the impact of urban development on wind flows [32-37], not paying due attention to green infrastructure as a natural obstacle.

This article discusses the effect of trees on a wind field in a city. The basics of the influence of trees on wind flows were described in the late 19th century by V.V. Dokuchaev and G.N. Vysotsky [38]. They developed a concept of forest belt to manage various climatic and agricultural problems, such as drought, even distribution of snow, low humidity of fields or high speeds of wind flows. They also found that forest belts contribute to a 40-50% reduction in wind speed.

Unlike other obstacles, trees have a more complex and diverse structure. Wind flows near trees and directly inside their vegetation cover are characterized by the formation of vortices, high resistance, and complex turbulence [39-41]. For reliable numerical modeling, it is customary to consider vegetation as a porous surface.

The field of the research on the influence of trees on wind flows remains under-explored at the time of writing of this article. Moreover, there are many works describing the effect of wind on trees [42-44]. In addition, the bulk of the work related to the influence of wind on trees is focused on windthrow in natural forests [45-46].

The aim of this research is to study the influence of various parameters of trees on the behavior of wind flows in urban environments by using the RUDN University campus as an example.

2. Materials and research methods
This study was conducted on the RUDN University campus located in the south-west of Moscow (Figure 1 (a)).

To obtain transparent results, meteorological data for May 29, 2017 when extremely high wind speed was observed in Moscow were used [47]. The average velocity of the incoming flow in the experiments is about 12 m/s, and the direction is southwest.

To simulate wind flows in this work, the EnviMet software package was used [48]. This tool is based on the method of computational fluid dynamics using the Navier-Stokes equations averaged by Reynolds [49-54].
Figure 1. Research area. Moscow map with marked RUDN University location (a). Research site map (RUDN University), green points are trees, grey polygons are buildings, numbers are building heights (b). 3D map of research site created by EnviMet software (c).

2.1. Input data
To simulate wind flows using EnviMet, the following inputs were required:

- Shapefile of buildings (polygon), with the height values specified in the attribute table for each building.
- Shapefile of trees (points), with identification numbers indicated in the attribute table.
- Meteorological data in csv format.

Shapefiles were obtained through fieldwork and OSM (Open Street Map) data (a similar technology was described in [55]. Measurements of the heights of buildings were carried out, the tree species present on the site, their height, crown width were determined.

Meteorological data were provided by the observatory of Moscow State University. The experimental site was a plot of 615 m by 333 m. There are 815 trees and 3 buildings on the site (Figure 1 (b), (c)).

2.2. Description of species
Ten hypothetical tree species with different proportions were identified for a clear understanding of the influence of parameters on the behavior of wind flows. The hypothesis was that the following parameters mainly influence the behavior of the wind: tree height, crown width, crown height above Earth’s surface (trunk height), LAD (Leaf Area Density) index, and crown shape. The hypothesis is based on the experience of studying the effects of tree parameters on the risk of windthrow [56-59]. Based on these parameters, species in Table 1 were distinguished. The crown shape was set to be the same for all species. The effect of this parameter will be described later. Table 2 shows the objects of comparative analysis for these tree species.
Table 1. Parameters of tree species.

| ID | 31  | 32  | 33  | 34  | 35  | 36  | 37  | 38  | 39  | 40  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Tree Height, m | 5   | 5   | 10  | 10  | 10  | 10  | 10  | 15  | 15  | 10  |
| Crown Width, m  | 3   | 3   | 7   | 7   | 3   | 3   | 11  | 11  | 7   | 7   |
| Trunk Height, m | 1   | 3   | 1   | 3   | 1   | 3   | 2   | 4   | 1   | 1   |
| LAD            | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 0.3 | 2   |

Table 2. Subject of the comparison.

| ID | 31  | 32  | 33  | 34  | 35  | 36  | 37  | 38  | 39  | 40  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 31 | -   | -   | -   | Height | -   | -   | -   | -   | -   | -   |
| 32 | *   | -   | -   | -   | -   | -   | -   | -   | -   | -   |
| 33 | -   | -   | -   | Trunk | Crown | -   | -   | -   | -   | -   |
| 34 | -   | -   | *   | -   | -   | Crown | -   | -   | -   | -   |
| 35 | *   | -   | *   | -   | -   | Trunk | -   | -   | -   | -   |
| 36 | -   | *   | -   | *   | -   | -   | -   | -   | -   | -   |
| 37 | -   | -   | *   | -   | -   | -   | -   | Trunk | -   | -   |
| 38 | -   | -   | -   | *   | -   | -   | -   | -   | -   | -   |
| 39 | -   | -   | *   | -   | -   | -   | -   | -   | -   | LAD |

Modelling was carried out for each of the selected tree species. In each experiment on the plot trees of one specific species were placed at the same positions for all experiments.

2.3. Data analysis

The analysis included comparisons of the wind fields of the experimental sites. The site consisted of a grid with a resolution of 3m/3m/3m for each cell. The total area of the site is 204795 m². EnviMet provides results for each cell. That is, the wind speed in each grid cell is known. The following indicators were analysed:

- The average speed on the site.
- The maximum speed on the site.
- The area with the observed wind speed in the selected ranges (on the one hand, ranges from 0 to 18 m/s, in increments of 1 m/s; on the other hand, ranges from Table 3).

Table 3. Wind speed ranges.

| Wind speed range | Effect          |
|------------------|-----------------|
| 0-6 m/s          | Low aeration    |
| 6-12 m/s         | Perfect condition|
| 12-13 m/s        | No effect       |
| >13m/s           | Increase in wind speed |

Also, in order to assess how much the situation on the experimental site changed as a whole, depending on one or another parameter of the tree, the Student’s t test was calculated for related samples. An area without trees was modelled. Further, the wind speed values in each grid cell of this site were subtracted from the wind speed values in the corresponding cells of the analysed site. Then the area with positive and negative values was calculated. The positive values show how much the speed has increased (increasing coefficient), and the negative ones, how much it has decreased (decreasing coefficient). After that, the mean was found for the positive and negative values. Based on
the data obtained, we can say what is the size of the site area where there is a decrease or increase in the wind speed and how significant this decrease/increase is.

3. Results and discussion

3.1. Trunk height

This part is a comparison of sites 31 and 32 for the effect of crown height above ground level (trunk height).

To begin with, consider the incoming flow velocity for each experiment and the average wind speed observed at the site. Based on the data presented in Table 4, the incoming flow velocity ranges from 11.7 m/s to 12.6 m/s, while the average speed increases with height from 8.36 m/s at a level of 1.5 meters up to 10.9 m/s at a height of 10.5 meters above the ground. It should be noted that the difference in the average speed between sites 31 and 32 decreases with increasing altitude.

Table 4. Mean, maximum, and input wind speed on TS-31 and TS-32.

| ID, height, m  | TS 31, 1.5m | TS 32, 1.5m | TS 31, 4.5m | TS 32, 4.5m | TS 31, 10.5m | TS 32, 10.5m |
|----------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Mean speed, m/s| 8.36        | 8.97        | 8.94        | 9.30        | 10.89       | 10.90       |
| Input speed, m/s| 11.70      | 11.70       | 12.40       | 12.40       | 12.60       | 12.60       |
| Maximum speed, m/s| 14.06    | 15.14       | 14.69       | 15.11       | 16.59       | 16.53       |

Figure 1 (a) shows the percentage of the total area where wind speeds are observed in the indicated ranges at heights of 1.5, 4.5, and 10.5 meters. This diagram shows well that at a pedestrian height trees with a crown below 1.5 meters reduce the number of zones with increased wind activity and proportionally increase the number of zones with a wind speed below the input speed. The difference in areas with a wind speed of 10-11 m/s at a height of 1.5 m was approximately 15,000 sq. meters.

At a height of 4.5 meters the difference begins to decrease significantly, and at an altitude of 10.5 m it is practically absent. But if the height of these tree species is 5 m, it should be noted that there is a difference in the wind fields at a height of 10.5 meters (although at first glance it should not be) due to the turbulence of wind flows. This means that the changing behaviour of the downstream flows affects the upstream, just as the variability of the upstream affects the behaviour of the downstream.

A comparative analysis of sites 33 and 34 shows an identical effect of the trunk height on the wind behaviour. On site 33, a decrease in the zones with a speed approximately equal to the speed of the incoming flow is noted, and the zones with a low aeration level increase proportionally. At the same time, the difference in the wind fields of sites 33 and 34 is more pronounced (in comparison with sites 31 and 32) due to the fact that the trees in these sites have crowns more than twice as wide (Figure 1 (b)).

In contrast to the comparison of sites 31 and 32, at the level of up to 4.5 meters the difference in the area with a speed below 6 m/s between sites 33 and 34 is much greater. This phenomenon can lead to an increased risk of formation of "stagnant zones", which negatively affects the general ecology of the city and the health of the citizens.

Also, for sites 31-34 the Student's t-test for related samples described earlier was calculated. After that, the values were obtained which are presented in Figure 1 (c). In this case, we can see how strongly the trunk height affects the wind field as a whole. At the level of 1.5 meters there is a significant decrease in the wind speed on sites 31 and 33 relative to sites 32 and 34, respectively. This difference decreases at a height of 4.5 meters and almost disappears at a height of 10.5 meters. However, the difference in obstacles at the trunk level affects the wind field even at a level of 10 meters.
A comparative analysis for sites 33 and 34 showed a wind behaviour trend similar to the previous sites in this section. The only exception was the increase in the effect, as in the case of sites 33 and 34.

3.2. Crown width

A comparative analysis of sites 33 and 35 was carried out for the effect of the crown width on the wind activity. Table 5 shows the mean and maximum wind speed relative to the input flow speed at a height of 0.3 to 13.5 meters. The average speed on site 33 is significantly lower, which is a consequence of the increase in the area of trees as a natural obstacle due to the increase in the crown width. The given dependence is quite logical. Of greater interest is the increase in the maximum speed on site 33. This phenomenon is explained by the fact that trees located close to each other create turbulent zones, which leads to the formation of eddies. On site 35 with a smaller crown width there is more free space for the passage of wind currents.

It turns out that the crown width simultaneously leads to an increase in zones with low aeration level and an increase in wind speed.
Table 5. Mean, maximum, and input wind speed for sites TS-33 and TS-35.

|      | TS-33 |      |      |      |      |      |      |
|------|-------|------|------|------|------|------|------|
|      | 0.3m  | 0.9m | 1.5m | 2.7m | 4.5m | 7.5m | 10.5m|
| mean speed, m/s | 6.81 | 6.91 | 7.00 | 7.16 | 7.39 | 7.96 | 8.94 | 10.62|
| input speed, m/s | 7.93 | 10.42 | 11.65 | 12.36 | 12.40 | 12.46 | 12.52 | 12.58|
| maximum speed, m/s | 13.76 | 14.39 | 15.06 | 15.41 | 15.40 | 15.27 | 15.39 | 15.50|
|      | TS-35 |      |      |      |      |      |      |
| mean speed, m/s | 7.95 | 8.10 | 8.21 | 8.41 | 8.65 | 9.12 | 9.79 | 10.97|
| input speed, m/s | 7.92 | 10.41 | 11.64 | 12.35 | 12.39 | 12.45 | 12.51 | 12.58|
| maximum speed, m/s | 13.47 | 13.67 | 13.79 | 14.38 | 14.53 | 14.43 | 14.15 | 14.70|

Table 6 shows the percentages of the total area for the zones with a specified wind speed ranges to estimate the scale of the impact described above. It should be noted that the area of the zones with low level of aeration on site 33 is twice as large as on site 35 and is as much as 37 percent at pedestrian level. At the same time, trees with a wide crown at a level of 10.5 m lead to the formation of a significant zone with increased wind activity, about 10,500 sq. meters.

Table 6. Exposure area in analysed ranges on sites TS-33 and TS-35 at different heights.

| Area TS-33, % | 0.3m | 0.9m | 1.5m | 2.7m | 4.5m | 7.5m | 10.5m |
|---------------|------|------|------|------|------|------|-------|
| 0-6m/s        | 36.8 | 37.0 | 37.1 | 36.6 | 35.3 | 30.2 | 20.5  |
| 6-12m/s       | 54.7 | 54.1 | 53.5 | 48.7 | 45.5 | 45.4 | 49.0  |
| 12-13m/s      | 1.5  | 1.9  | 2.4  | 7.6  | 11.9 | 15.5 | 20.0  |
| >13m/s        | 0.02 | 0.03 | 0.1  | 0.2  | 0.6  | 2.2  | 5.1   |

| Area TS-35, % | 0.3m | 0.9m | 1.5m | 2.7m | 4.5m | 7.5m | 10.5m |
|---------------|------|------|------|------|------|------|-------|
| 0-6m/s        | 18.8 | 18.5 | 18.6 | 18.3 | 17.5 | 14.7 | 10.7  |
| 6-12m/s       | 74.0 | 74.0 | 73.6 | 68.1 | 63.1 | 59.1 | 58.6  |
| 12-13m/s      | 0.2  | 0.5  | 0.8  | 6.5  | 12.4 | 18.8 | 22.3  |
| >13m/s        | 0.004| 0.009| 0.02 | 0.2  | 0.3  | 0.7  | 3.1   |

Similarly to the analysis from the previous section, the Student's test was calculated for related samples on sites 33 and 35. As one can see from the results presented in Figure 2, site 33 shows a significant decrease in the wind speed in comparison with site 35. At the same time, the ratio of the areas with increasing and decreasing speed is relatively the same. This result is similar to the results described in the previous section, except that in the case of a change in the crown width the difference in the wind fields remains at levels up to 13 meters and above.
Figure 3. T-Test for sites TS-33 and TS-35 (a). T-Test plot for TS-31 - TS-35 (b), black numbers show exposure area in % (b). Exposure area for wind speed >12m/s on sites TS-31 and TS-35 (c).

A comparative analysis of sites 34 and 36 gave similar results, only with a smaller difference.

3.3. Tree height

Comparative analysis of experimental sites 31 and 35 for the effect of tree height. Table 7 shows the input flow, average and maximum wind speed values at heights of 2.7 m, 7.5 m, and 10.5 m. At a level of 2.7 m the values are approximately the same, since the field of obstacles at the indicated height is the same, small deviations exist only due to the turbulent influence of the overlying wind flows. At a height of 7.5 meters on site 31, the average and maximum speeds are noticeably higher than on site 35, due to the fact that the tree height on this site is 5 meters.

Table 7. Mean, maximum and input for sites TS-31 and TS-35 on different height.

| TS/height | TS-31, 2.7m | TS-35, 2.7m | TS-31, 7.5m | TS-35, 7.5m | TS-31, 13.5m | TS-35, 13.5m |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| Mean speed | 8.86        | 8.32        | 10.21       | 9.12        | 11.69       | 10.97       |
| Input speed | 12.36      | 12.35       | 12.50       | 12.45       | 12.59       | 12.58       |
| Maximum speed | 14.33      | 14.04       | 15.78       | 14.43       | 16.68       | 14.70       |

The most interesting results are obtained at 13.5 and 16.5 meters. At this height, the field of obstacles on sites 31 and 35 is the same, since the tree height is 5 and 10 meters, respectively. At the same time, the turbulence of the flows created by the trees spreads to a level exceeding the tree height,
which creates a noticeable increase in the zones with a speed above 12m/s on site 31 relative to site 35 (Figure 3 (a)).

In addition, the calculation of the Student’s t-test for related samples was carried out (Figure 3 (b)). The results of this analysis show that on 35 at an altitude of 13.5 inclusive, the increasing coefficient relative to site 33 is significantly higher. However, the area of zones with increased wind speed on site 33 is 2-2.5 times higher at the same height. It follows that high trees increase the average maximum speed on the site but reduce the overall speed. On the other hand, at altitudes up to 4.5 meters inclusive, the average minimum wind speed on site 31 is lower. At a height of 10.5 and 13.5 meters on site 35, both increasing and decreasing coefficients are higher. In this case, the average maximum wind speed on site 35 is higher and the average minimum wind speed is lower. At the same time, at a height of 16.5 meters the situation is opposite.

In addition, the results obtained demonstrate a strong influence of the tree height on the overlying (above the tree level) flows, significantly changing the wind field. A comparative analysis of sites 32 and 36 gave approximately the same results as in the case of 31 and 35. Only the difference in the average speed increased.

3.4. LAD index
An analysis of sections 39 and 40 on the influence of the LAD index on the behaviour of wind currents was carried out. Trees in the sites have the same parameters of height, crown width, and trunk height, but radically different LAD indexes. For site 39 LAD = 0.3, and for site 40 LAD = 2.

Figure 4 shows wind field maps for sites 39 and 40 at a height of 4.5 meters. The major differences are clearly visible. In site 40, on the one hand, the area of zones with insufficient aeration (shown in blue) is significantly larger, and on the other hand, the area of zones with increased wind activity is larger. In addition, in site 40 the maximum speed is higher than in site 39 (Table 8). That is, it turns out that high density of the canopy is a rough barrier to the wind flows.
**Figure 4.** Wind field maps for different LAD indexes: LAD=0,3 for TS-39(a) and LAD=2 for TS-40(b), the height is 4.5m. Black polygons are buildings, green polygons are trees.

**Table 8.** Mean, maximum, and input wind speed for sites TS-39 and TS-40 at different heights.

|          | TS-39      |          |          |          |          |          |          |          |          |
|----------|------------|----------|----------|----------|----------|----------|----------|----------|----------|
|          | 0.3m       | 0.9m     | 1.5m     | 2.7m     | 4.5m     | 7.5m     | 10.5m    | 13.5m    |          |
| mean speed, m/s | 7.20     | 7.34     | 7.46     | 7.65     | 7.91     | 8.40     | 9.28     | 10.45    |          |
| input speed, m/s | 13.42    | 13.60    | 13.73    | 13.84    | 13.88    | 13.86    | 14.06    | 15.07    |          |
| maximum speed, m/s |          |          |          |          |          |          |          |          |          |
| TS-40    | 0.3m       | 0.9m     | 1.5m     | 2.7m     | 4.5m     | 7.5m     | 10.5m    | 13.5m    |          |
| mean speed, m/s | 6.63     | 6.71     | 6.79     | 6.93     | 7.16     | 7.72     | 8.73     | 10.53    |          |
| input speed, m/s | 14.77    | 15.38    | 15.99    | 16.26    | 16.27    | 16.14    | 16.23    | 16.22    |          |

**4. Conclusions**

Within the framework of this study, an assessment was made of the influence of tree height, crown width, crown height above ground level, and the LAD index on the behaviour of wind flows. A strong variability of the wind field was revealed at various values of the indicated parameters. Trees with low...
canopy create more zones of reduced aeration at the pedestrian level, and the zones with a speed equal to the speed of the input flow have decreased. At the same time, at a level of 10 meters an increase in the zones with high wind activity was also revealed. Trees with a wide crown create a powerful barrier to wind flows, resulting in a large area with low aeration. On the other hand, wide crowns of neighbouring trees lead to the formation of wind gusts. Due to the turbulence of wind flows, the height of a tree can affect the wind field even at the pedestrian level. In general, low trees create a risk of wind gusts at the pedestrian level. In addition, a strong influence of the LAD index on the wind field was revealed. Trees with a high LAD value, due to their high density, create tough barriers comparable to a building. This leads to the formation of stagnant zones, as well as to a significant increase in the maximum wind speed.

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