The impact of tree clusters on air circulation and pollutant diffusion-urban micro scale environmental simulation based on ENVI-met

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Abstract. For urban planners, trees play a role in improving landscape quality, but their impact on urban ventilation is often ignored. By using the three-dimensional microclimate model ENVI-met, this article simulates 14 situations with different variables, aims to re-examine the impact of vegetation cover on aerodynamic effect. The results show that trees have a resistance effect on air flow, Especially the ratio of tree spacing/canopy width related to the continuous vortex area have a significance impact on wind speed, which is needed to be considered in urban planning of vegetation layout. Moreover, the distinguished theories under both conditions whether there is buildings or not are analysed, inspiring the planners and researchers to consider the relationship and discrepancy between different scales.

1. Introduction
Rapid urbanization has accelerated air pollution and has become a major factor affecting citizens’ quality of life. [1] Traffic-related emissions are one of the main factors that cause urban air pollution. [2] As a result, urban vegetation is widely used as one of the mitigation methods to deal with the threat of urban residents’ air particulate matter (PM) pollution to public health. [3] In order to reduce population exposure, vegetation barriers composed of hedges and/or trees are usually installed near roads to protect pedestrians from traffic-related pollutants. [4] However, local air circulation is affected by the resistance imposed by urban vegetation. [5]

Vegetation has been found to reduce wind speeds, which leads to obstruction of the canyon’s ventilation, and as a result, the concentration of particulate matter increases. [6] Some studies have been done in this area. Five common avenue tree species have been tested to study how dynamic tree growth affects three aspect ratios in street canyons (H / W = 0.45, 0.9 And 1.8) PM concentration distribution. [7] The impact of vegetation barriers on the spread of roadside air pollution was investigated and the best vegetation barrier height was found to effectively reduce traffic pollutants on slow lanes of urban streets.[8]

Although the influence of trees on street ventilation has been described in the literature, there is little research on the relationship between tree layout and tree species selection. This study aims to evaluate the impact of trees on air quality under different wind speeds, tree spacing, cross-sectional height, and the presence or absence of buildings, in order to provide certain reference significance for urban planners to develop forestry management practices.
2. Methodology

2.1. Basic design of the Envi-met model

ENVI-met consists of three sub-models: interactive one-dimensional boundary model, three-dimensional atmospheric model, and three-dimensional/one-dimensional soil model. The one-dimensional boundary model is mainly used for the boundary conditions of the three-dimensional atmospheric model. The three-dimensional atmospheric area is divided into \( I \times J \times K \) rectangular grids with a size of \( \Delta x \times \Delta y \times \Delta z \). In the grid unit, the distance between \( \Delta x \) and \( \Delta y \) on the horizontal plane remains unchanged. In order to more accurately simulate the exchange process between the atmosphere and the ground, which has a significant impact on the ground microclimate, the lowest grid unit is divided into five sub-grid units, which are vertically expanded to 0.2\( \cdot \Delta z \), and all other grid units have the same height \( \Delta z \). [9]

2.1.1. Calculation of wind flow

The temporal and spatial development of the wind speed and direction is calculated using the three-dimensional non-hydrostatic Navier-Stokes equations. Local source/sink terms are used to simulate the wind resistance of semi-permeable obstacles, which in our case refers to trees. When air penetrates through the porous body, a pressure gradient will be generated along the direction \( i \) of the wind component \( u_i \) (\( u_i = u, v, w \), where \( i = 1, 2, 3 \)). The effect of this pressure gradient on wind can be described as:

\[
S_{ui}(x, y, z) = \frac{\partial p}{\partial x} = c_{d,p} LAD(x, y, z) u W(x, y, z) u W(x, y, z)
\]

(1)

LAD is the leaf area density \([m^2 / m^3]\), which is set in the vegetation model distinguished by different tree species in the distribution of 3D space. Therefore, this parameter have an impact on the wind speed on planes of different height. \( c_{d,p} \) is the mechanical resistance coefficient of the leaf, and \( W(x, y, z) \) is the average wind speed in the grid unit. The mechanical resistance coefficient is set to \( c_{d,p} = 0.2 \), which is an average number of the real tests.

2.1.2. Vegetation model

The direct heat flux, evaporation flux and transpiration flux of the interaction between vegetation and the atmosphere are considered in the model. Furthermore, the aerodynamic drag \( r_a \) is a function of the blade diameter \( D \) and the wind speed \( W \).

\[
r_a = A \left( \frac{D}{W} \right)
\]

(2)

Parameter \( A \) and \( D \) depends on the type of plant. From this equation we can see that the LAD value and wind speed are two most significant parameters in our simulation, also the variables in our study.

2.2. Definition of test cases

2.2.1. street configuration and pollutants

The plane is divided into 50\( \times \)50\( \times \)30 grids, the distance between the grid points is 2 meters, covering a three-dimensional space of 100m\( \times \)100m\( \times \)60m, in which the width of the carriageway is set to 14m, and two linear PM10s release sources are set in the center of the carriageway. The release rate is 11.3 mg/m\( \times \)s, which is in line with the PM10 emissions in car exhaust under the condition of moderate traffic flow during the morning peak period. In order to better observe the changes in the concentration of pollutants, the sidewalk is set to be wider, 20m on each side.

2.2.2. Meteorological conditions

The location of climate simulation is selected in Qingdao, UTC/GMT+08:00, latitude 36.07°, longitude 120.33°, the temperature and humidity data of Qingdao’s daily summer weather are selected (data source is the National Greenhouse Data System), The initial
atmospheric temperature 25.1℃, and the relative humidity 77% are set in our case. The wind direction is set to the positive east wind direction, with the speed being 3m/s and 1m/s at a distance of 10m from the ground.

2.2.3. Vegetation coverage The deciduous vegetation Privet is selected as the common tree specie among the street trees in Qingdao, of which the crown height and width is both 5m, meaning the aspect ratio is 1. The carbon dioxide absorption type is C3. Furthermore, the leaf area density (LAD) simulated in CFD is 0.1m²/m³ to 4m²/m³, with the average value being 1m²/m³. [10] The leaf area density (LAD) set in our simulation is 0.7, and the leaf reflectivity is 0.3. The root depth is 2m covering 10m in diameter. The interval of street trees is set to 10m, 8m and 6m.

2.3. Overview of model simulation
The model was run in three sets of simulations, divided into 14 situations. The first group is when there are no buildings on both sides of the street, in which trees are separated by 10m. When the wind speed is 1m/s and 3m/s respectively, the change of wind speed at different screenshot heights (1.4m, 1.8m, 3m) is simulated and presented. The second group is the change of wind speed at different screenshot heights (1.4m, 1.8m, 3m) when there are no buildings, the trees are 8m and 6m apart, and the wind speed is 1m/s, besides, under this condition, there is pollution Concentration analysis with and without trees. The third group of streets has buildings on both sides, and the difference in wind speed with and without trees is analysed.

| Serial number | Wind speed interval | Section plane height | Simulated environment |
|---------------|---------------------|----------------------|-----------------------|
| 1             | 1m/s                | 10m                  | 1.4m                  | No buildings |
| 2             | 1m/s                | 10m                  | 1.8m                  | No buildings |
| 3             | 1m/s                | 10m                  | 3m                    | No buildings |
| 4             | 1m/s                | 8m                   | 1.4m                  | No buildings |
| 5             | 1m/s                | 8m                   | 1.8m                  | No buildings |
| 6             | 1m/s                | 8m                   | 3m                    | No buildings |
| 7             | 1m/s                | 6m                   | 1.4m                  | No buildings |
| 8             | 1m/s                | 6m                   | 1.8m                  | No buildings |
| 9             | 1m/s                | 6m                   | 3m                    | No buildings |
| 10            | 3m/s                | 10m                  | 1.4m                  | No buildings |
| 11            | 3m/s                | 10m                  | 1.8m                  | No buildings |
| 12            | 3m/s                | 10m                  | 3m                    | No buildings |
| 13            | 1m/s                | 10m                  | longitudinal section  | Street canyon |
| 14            | 1m/s                | No trees             | longitudinal section  | Street canyon |
3. Results

When the interval of trees is 10m, because the distance is much larger than the width of the canopy (the width of the canopy is 5m), the trees almost only have an impact on the wind speed within their canopy at a wind speed of 1m/s. A small vortex area is formed at the front and back of the canopy. In the case of high wind speed (3m/s), the effect of reducing the wind speed is more obvious. Within 7m of the windward surface of the canopy and 25m of the leeward surface of the canopy, there is a significant reduction effect, moreover, the wind speed between canopies is reduced at the same time.

In the case of an interval of 6m, since the interval between trees is similar to the width of the canopy, tree spacing/canopy width = 1.2, a continuous deceleration zone is formed before and after the entire row of trees. This effect is most obvious at a height of 1.4m from the ground, affecting 25m in front of the canopy, and two rows of trees in between, that is, the wind speed in the carriageway is lower.
After adding buildings on both sides of the street in the model, it can be found that the buildings reduce the wind speed in the street as a whole, especially the leeward side of the east side building, where the wind speed is already less than 0.07 m/s, but in the middle of the street, part of the airflow enters the street from top to bottom due to the air pressure difference, which increases the wind speed of this part of the carriageway and sidewalk. In the case of trees set in street, the airflow in the middle of the street is once again blocked. It can be seen that the impact of trees has reached a height of 8m, making this part of the wind speed reduced by about 0.2m/s.

When there are 18 m high buildings on both sides, the trees also reduce the wind speed in the street, especially in the middle of the street, which is the emission location of the car exhaust pollution source. This makes the dilution and diffusion of pollutants difficult. In the case of no trees, the pollutant has dropped to 5.2 g/m3 before reaching the sidewalk, while in the case of trees set in street, the concentration of the pollutant drops from 6.2 g/m3 to 5.2 g/m3 only after reaching 10 m depth of the sidewalk.

4. Discussion

4.1. The blocking of air flow by trees in different conditions
In the Envi-met simulation, we simulated and calculated several ideal situations. In the case of streets without buildings and streets with buildings, although the mechanism is different, the final result is that the trees play a role in reducing street ventilation. Although the specific movement of the airflow in the street canyon is very complicated, vortex areas of different sizes and complex turbulence will be generated due to buildings, obstacles, etc. But in general, these airflows must follow the conservation of momentum when passing through the trees, transferring a part of the momentum to the blades and stomata, so that the final speed is reduced.

4.2. The relationship between tree spacing/canopy width and continuous vortex area
It is worth noting that although there are analyses showing that planting trees at large intervals can greatly reduce the negative effect of street ventilation [11], But what we need to pay attention to is that the interval distance is not an independent parameter. The more important parameter should be a ratio $r = \frac{\text{interval distance}}{\text{canopy width}}$. The closer this value is to 1, the greater the blocking effect of trees on the airflow, and there should be an obvious transition point between interval planting and dense planting.
planting, which will transform the effect of trees on airflow from a single tree to a whole, forming a continuous vortex area on the windward side of the trees. This vortex area will greatly expand the influence of the trees on the air blocking effect.

4.3. The influence of trees on wind speeds at different heights
No matter whether the trees form a cluster or not, they all have the greatest hindrance to the wind speed at a height of 1.4m, which is close to the height of human breathing area. The privet tree is 5m high and the leaf area density reaches the highest value at the plan of 2m above the ground, where the wind speed is also relatively low due to the friction of the ground. We speculate that different tree species will have the best blocking height. At this height, the wind speed drops the fastest and the range of decline Maximum, this optimal blocking height should be related to the height of trees, the longitudinal distribution of leaf area density and other parameters.

5. Conclusion
This paper establishes the ENVI-met model to simulate the street wind speed and pollutant concentration in Qingdao. The result shows different theories under different conditions, but in the aspect of ventilation, the trees always have the negative influence. To be specific, the scale of vortex area is closely related to the ratio tree spacing/canopy width, which implicates that for different species of trees, intervals should be set diversely keeping the ratio above 1. Considering trees already planted of which the ratio below 1, air pollution can be mitigated by trimming the canopy. As for the height of the trees, it should be considered with the condition of the sidewalk in order to maintain airflow of breathing height to dilute the pollution. This result can provide some guidance for urban planners in the layout of trees, in order to create a healthier urban environment.

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