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Analysing the influence of different street vegetation on particulate matter dispersion using microscale simulations

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ABSTRACT

Urban vegetation can be viewed as compensation to the environmental drawbacks of urbanization. However, its ecosystem function is not well known and, for urban planning, vegetation is mainly considered as an element of urban design. This article argues that planning practice needs to re-examine the impact of vegetation cover in the urban fabric given our evaluation of vegetation's effects on air quality, including the law. In this paper, we use the method of microclimate simulation in Beijing city as an example, using the three-dimensional microclimate model ENVI-met, to evaluate these effects. The results are summarized as follows: (1) the concentration of pollutants in the winter is generally greater than that of the summer, (2) higher wind speed favors ventilation inside the streets, reducing the concentration of particulate matter, and (3) block effect on particulate matter of different vegetations which corresponds to the structures are shrub and grass vegetation combine > bushes and trees combine > shrub > tree > no greenery.

Keywords: Particulate matter; Road vegetation; Microclimate simulation

1. Introduction

This article studies the dispersion of particulate matter on streets from the interaction among roads, buildings, and vegetation on the purpose of urban road greening design. At present, the domestic and international methods for the study of the convective and diffused particulate matter in urban street canyons mainly include field observation, wind tunnel experiment, and numerical simulation. In field measurements, Chan and Kwok [1], in Hong Kong, found that the concentrations of PM10 and PM2.5 were exponentially distributed in height; Ariel [2] measured the concentration of pollutants in parts of urban areas of Argentina, and obtained the distribution law; Qi [3] set up three sampling points to compare the concentration of the forest belts with the same width and different width on both sides of the green belt based on the city of Zhengzhou. Liu et al. [4] took PM2.5 and PM10 of air in Beijing as the research object and set two sampling points in Cheng Fu Road East and the Qian Men. In the field of wind tunnel experiment, Chinese scholar Zhang et al. [5] conducted a wind tunnel experiment on a complex block in Macao, and analyzed the dispersion law of pollutant emissions from automobile exhaust when smooth traffic and traffic jam. In numerical simulation, Sang et al. [6] used k-ε model to simulate the circulation on streets and its thermal structure. The innovation of this research is that it is the first simulation experiment to study the influence of different street vegetation on particulate matter dispersion conducted on urban streets.

The road vegetation can purify pollutants in the atmosphere effectively. In this paper, we used three-dimensional microclimate simulation software ENVI-met [7] as a tool to design different layout patterns of road vegetation and simulate matter dispersion (hereinafter referred to as PM10) under different environmental conditions and finally analyzed the influence of PM10 dispersion on streets of a variety of factors. Using microscale simulation should first consider different afforestation patterns and vegetation structures.

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In this paper, the road vegetation structure was divided into no greenery, tree, shrub, bushes and trees combine, tree, and shrub and grass vegetation combine. Meanwhile, three common width of streets and the aspect ratio of buildings on both sides (hereinafter referred to as aspect ratio) of Beijing were set up to 0.5, 0.9, and 1.2 which represent loose, compact, and very compact, respectively. Different layout patterns are conducted by microclimate simulation, respectively, under different weather conditions (temperature, humidity, wind speed, and wind direction) and simulate the dispersion of PM10 under combinations of different road vegetation layout patterns and different weather conditions by numerical simulation system.

2. Materials and methods

In this study, taking the city of Beijing as an example, the road layout was a typical form of block roads layouts, and the aspect ratio was set as three common street aspect ratios in Beijing. Regarding meteorological conditions, the southeast wind prevails in Beijing in the summer, so set the direction of the wind as 135°. The northwest wind prevails in Beijing in the winter, so set the direction of the wind as 315°. In all simulations, the source of pollution is 0.3 m (the average height of automobile exhaust emissions) and the diameter is 10 μm, and the constant emission rate is 100 μg/(s*m) (The data were measured according to the research team in winter and summer for 30 d in total. The PM10 emission rates were measured between 80 and 120 μg/(s*m), so 100 μg/(s*m) was taken as the average).

2.1. Introduction of ENVI-met

ENVI-met is a microscale climate model (fluid dynamics model) based on fluid and thermodynamics and microscale design. Use three-dimensional non-static mechanical model to simulate the interaction [8–10] of small-scale microenvironment. The model consists of three separate sub models and nesting grids. The sub models include a main 3D model, a soil model, and a 1D model (Fig. 1(a)) [11]. We used the version 3.1 in our study.

The model consists of a main 3D model and a 1D model, which simulates the atmospheric processes from the boundary layer to the height of 2500 m. The 3D model is subdivided into grid units (X, Y, and Z).The size of each dimension is resolution. ENVI-met provides four methods of dividing vertical grids. This paper selects the bottom subdivision schemes [12] (Fig. 1(b)).In vertical direction, all of the grid units have the same vertical extension of ΔZ, except five lowest small units that have longitudinal extension of $\Delta Z = 0.2\ \Delta Z$ in order to increase the precision of calculation of surface process and simulation of near surface. Details on parameters and equations are listed in Bruse [13] and Bruse and Fleer [14] and online manuals of scientific literature [15].

2.2. Experimental scheme

This study used ENVI-met, a microclimate simulation analyzing tool, and chose closed LBC [12] as turbulent boundary model. Firstly, set a 1D boundary model. Secondly, calculated the inflow boundary conditions

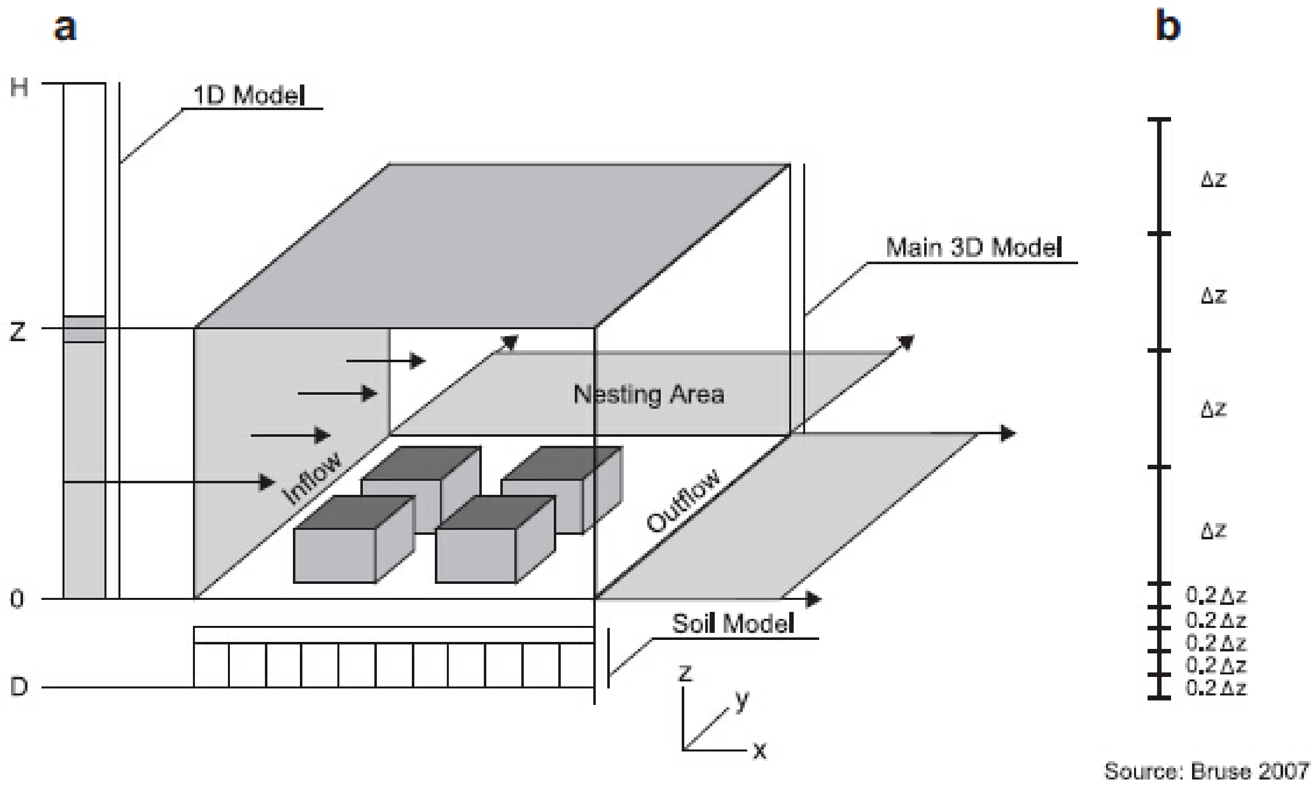

Fig. 1. Architecture of ENVI-met: (a) Model architecture and (b) vertical grid architecture (bottom subdivision scheme).

according to the customized background meteorological data and assign the results to all inflow boundary networks of 3D model domain. In the study, atmospheric humidity, absolute humidity, surface roughness, and the factors of the ratio of solar radiation cannot be measured. This paper uses default values of ENVI-met model. In simulation experiment, the area of simulation is 60 m × 22 m, the size of grid is 1 m × 1 m × 2 m, and the height of buildings on both sides of the city roads are 20 m.

2.2.1. Meteorological parameters

Using ENVI-met to simulate needs to define a set of meteorological parameters, the main parameters set as shown in Table 1.

2.2.2. Building and street configuration

This study defines three different aspect ratios (sectional drawing as shown in Fig. 2(a)). Height and width (H/W) are important factors to consider in modeling street canyon. *H* is the height of the building, and *W* is the width of the road. We chose to analyze the dispersion of pollutant particles of a wide street canyon (aspect ratio of 0.5) and two narrow street canyons (aspect ratios of 0.9 and 1.2). The choice of these aspect ratios are based on the research results of the street canyon flow field [16] and the typical street layout in Beijing [17].The aspect ratios are relatively large in dense streets. Wide streets (aspect ratio <0.5) usually have very few buildings on both sides. The highest aspect ratio of streets in Beijing is 1.2 which involves 10% of the streets in Beijing mainly located in dense and developed areas such as downtown and urban residential areas.

2.2.3. Sources of pollutants

Set two different pollution sources in the model. In narrow streets (e.g., the aspect ratio is 0.9), the pollution source is linear and located in the center of the street (Fig. 2(b) left). In the wide streets (aspect ratio is 0.5), the pollution sources are two which located parallel to the center line of the street (Fig. 2(b) right).

2.2.4. Vegetation cover

In this study, five vegetation covers were set on both sides of the road, including trees, shrubs, bushes and trees combine, shrub and grass vegetation combine, and no greenery. The central isolation belt (the aspect ratio is 0.5) is set as bushes and trees combine. In all vegetation simulations, trees or shrubs should be parallel to buildings and pollution sources and one grid width away from buildings. Shrubs should be set as continuous distribution. The distance between trees should be 4 m (minimum distance of border trees) (vegetation cover with aspect ratio of 0.9 in Fig. 2(c)).

3. Results and analysis

3.1. Air flow and particle dispersion in street canyons with no vegetation

Measure the dispersion of particulate matter of no vegetation streets before analyzing the effects of different vegetation configurations. Analyze different aspect ratios and wind directions in streets from the air flow and speeds of directions of Ux, Uy, and Uz. Fig. 3 shows the changes of winds on vertical directions with the condition of no vegetation, 10 m high from the ground and at the speed of 3 m/s of different directions. Negative values indicate downward flow, and positive value indicates upward flow. It can be seen from Fig. 3 that when the direction of wind is 135°, the air flow from buildings to streets, so there are mainly downward air on streets. The speed of wind at the direction of wind of 135° is lower than that of 315°, because of the mixture of downward and upward air. And a large number of downward and upward air flow changes as the aspect ratio changes. As the aspect ratio increasing, downward flow on streets is increasing with the direction of wind of 315°. In addition, the aspect ratio largely affects the flow of air. As the aspect ratio increasing, the air on streets is rarely mixed with the outside air which results in the reduction of ventilation on streets.

3.2. The result of particle dispersion

Fig. 4 simulates the dispersion of particulate matter at the wind speed of 1m/s and with no vegetation. The results

Table 1
The main parameters of the model

Parameter	Definition	Value
Meteorological conditions	Initial air temperature	288 K
	Relative humidity of 2 m	70%
	Specific humidity of 2500 m	4 g/kg
	Inflow wind direction	135° (summer), 315° (Winter) (at 10 m)
	Wind speed	1 m/s, 3 m/s (at 10 m)
Street configuration	Parallel to buildings on both sides	Aspect ratio: 0.5, 0.9, 1.2
	Type	Diameter of 10 μm
Pollution sources	Shape	0.3 m high line
	Speed	100 °g/(s*m)
	Height	10 m (tree), 1.5 m (hedge)
Vegetation settings	Leaf area density	0.2–2.0 m^2/m^3
	Lateral density	Continuous or discontinuous

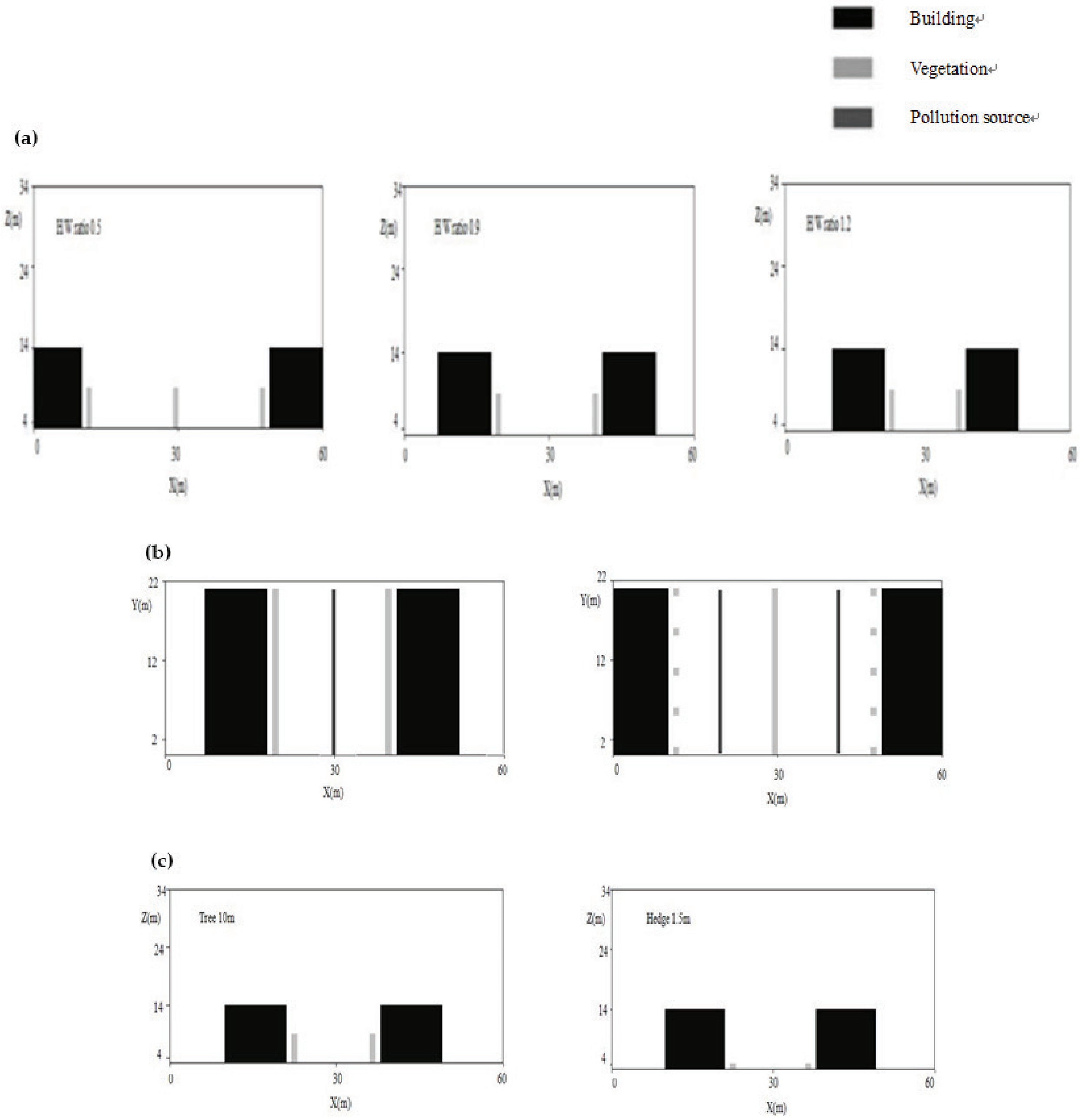

Fig. 2. (a) Cross section of all three aspect ratios, (b) plan view of model areas with (left) scenario with the widely spaced row of trees in the canyon with aspect ratio 0.9 and (right) scenario with continuous row of trees/hedge in the canyon with aspect ratio 0.5, and (c) a detailed view of the cross section with aspect ratio 0.9.

showed that the concentration of pollutants near the source of pollution was highest. As the distance from pollution source increasing, the amount of pollution is decreasing. It can be found by comparing two different inflow wind directions with same aspect ratio, the pollutant concentration was higher at the direction of 315° than that of 135°. When the wind direction is 315°, there are mainly downward flows on streets which may cause the decrease of internal and external gas exchange and the increase of concentration.

It can be found from the study that higher wind speeds (3 m/s) were better at reducing the concentration of particulate matter. As the aspect ratio increasing, the concentration of pollutants was increasing especially obvious at the direction of 315° on narrow streets (with aspect ratio of 0.9 and 0.2).

3.3. Vegetation effects on air flow and particle dispersion

In order to evaluate the effects of vegetation on particle dispersion on street canyons, no vegetation was regarded as the reference of other four vegetation structures. Fig. 5 simulates the changes of concentration of particulate matter at the wind direction of 135°and speed of 1 m/s. Set 1.5 m high of the grid unit to represent the particulate matter absorbed by human body.

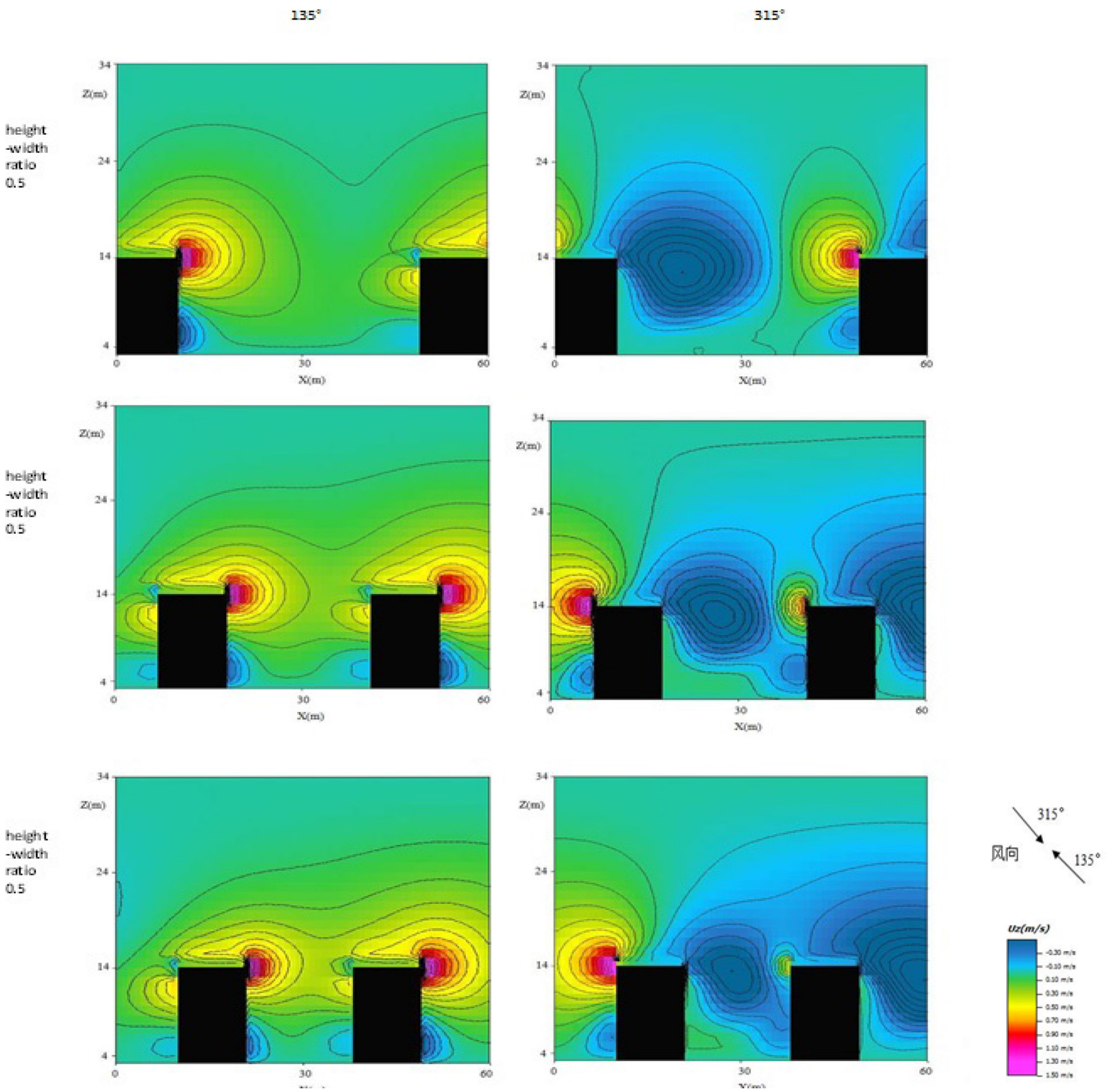

Fig. 3. Vertical wind flow (Uz) with a wind speed at 10 m of 3 m/s. Blue colors indicate downward flow, green to magenta indicate upward flow (distance between contour lines is 0.1).

The simulation results showed that the concentration of pollutants showed an increasing trend with the increase of aspect ratio under the same vegetation settings. When the aspect ratio was 0.5, the reduction of four vegetation structures is as follows: tree > shrub and grass vegetation combine > bushes and trees combine > shrub. When the aspect ratio was 0.9, the reduction of four vegetation structures is as follows: shrub and grass vegetation combine > bushes and trees combine > shrub >tree. When the aspect ratio was 1.2, the reduction of four vegetation structures is as follows: bushes and trees combine > shrub > shrub and grass vegetation combine > tree.

The size of the block effect can be given based on the above three cases which correspond to the following structure: shrub and grass vegetation combine > bushes and trees combine > shrub > tree > no greenery.

4. Conclusion and discussion

4.1. Combine the concentration of particulate matter and wind speed to observe

With the suppression in ventilation, the increase in concentration of plant-related particulate matter can be explained

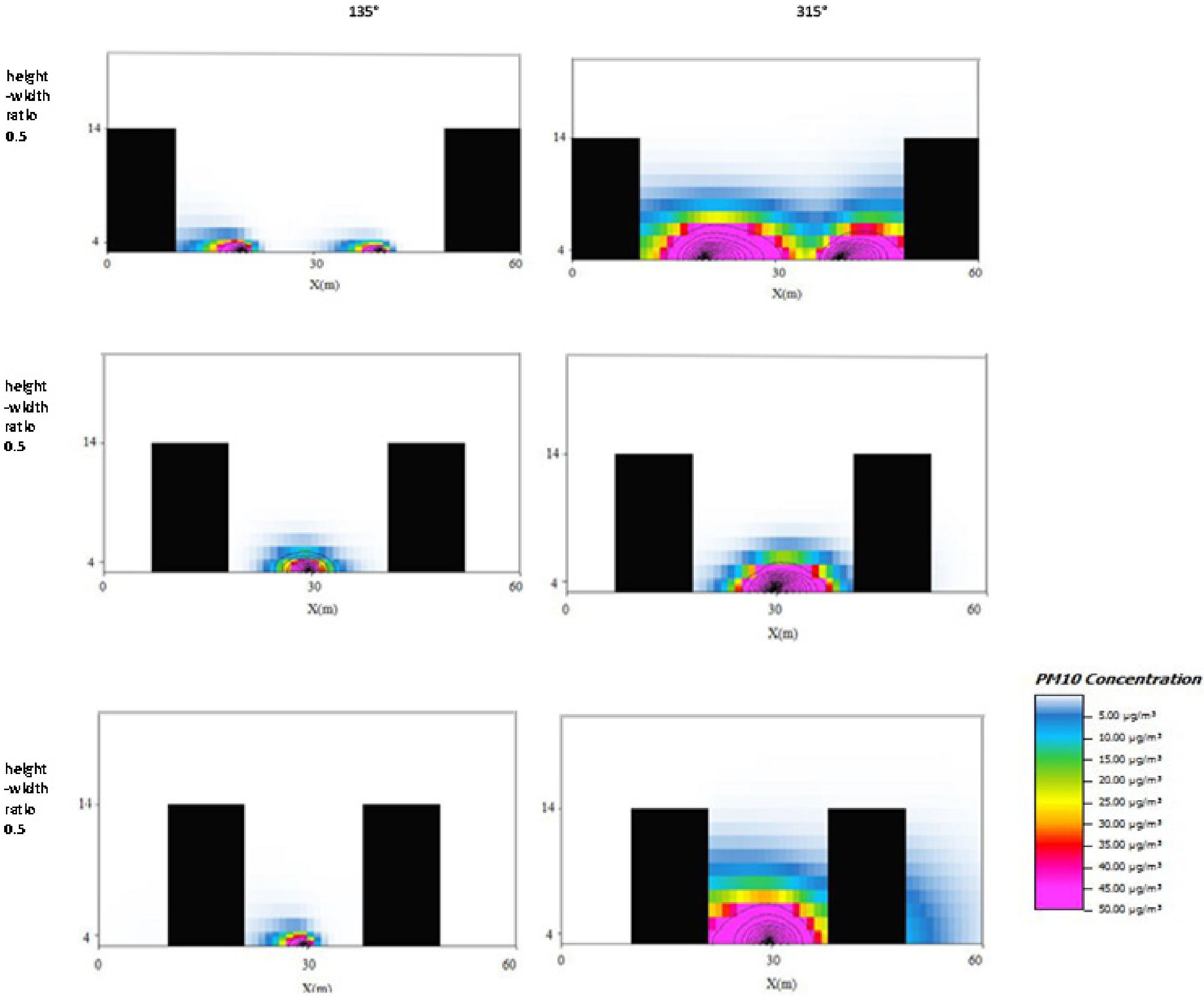

Fig. 4. Particle concentrations in the calm wind simulation (1 m/s) with different inflow directions (distance between contour lines is 0.5 μg/m³).

by wind speed and the decrease in air mixing. The effects on increasing of concentration by decreasing in wind speed were proved by Czáder et al. [18], De Maerschalck et al. [19], Gromke et al. [20], Ries and Eichhorn [21]. In general, decreasing in wind speed leads to reduction in air mixing on streets and fresh air inflows.

Fig. 6 shows the effects on wind speed changes of four vegetation conditions (simulated wind speed 1 m/s) when the aspect ratio was 0.9. It can be seen from the experiment that the effect of shrubs on air flow is about 6 m away from opposite, while the effects of bushes and trees combine and shrub and grass vegetation combine on air flow can reach 12–15 m.

When the wind direction is of 135°, four vegetation conditions to reduce the wind speed are as follows: tree > shrub and grass vegetation combine > bushes and trees combine > shrub. When the wind direction is of 315°, four vegetation conditions to reduce the wind speed are as follows: shrub and grass vegetation combine > bushes and trees combine > tree > shrub.

4.2. Changes in concentration of particulate matter with time

- The concentration of pollutants in winter is generally higher than that in summer. The reason may be that the weather in winter is dry and the use of coal is increasing and dust is serious. These result in higher concentration of the overall particulate matter [22–24]. The higher humidity in summer results in segments of particulate matter in atmosphere, so the concentration is relatively low.
- The influence of wind speed on concentration of pollutants. High wind speed is beneficial to ventilation which leads to lower concentration of pollutants [25–29]. Low wind speed is harmful to internal and external air mixture which leads to the increase of concentration.

4.3. Effects of different vegetation conditions on pollutant concentration changes

Block effect on particulate matter of different vegetations which corresponds to the structures are shrub and grass

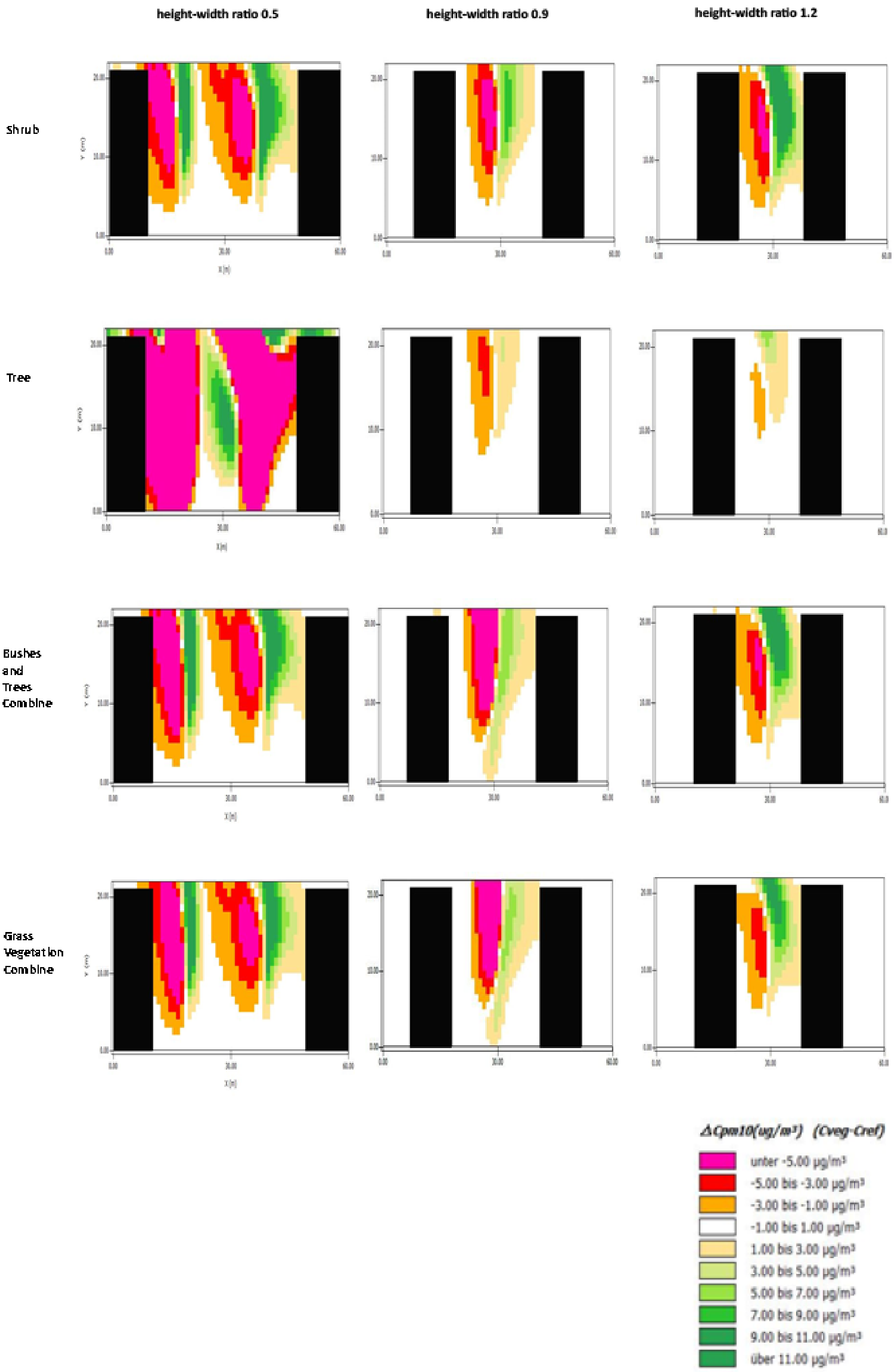

Fig. 5. Influence of vegetation on particle concentrations for inflow direction is 135°and wind speed is 1 m/s (grid cells at 1.5 m height). Comparison between the simulations without vegetation (reference case, Cref), with the hedge and the three tree scenarios (vegetation scenarios, Cveg).

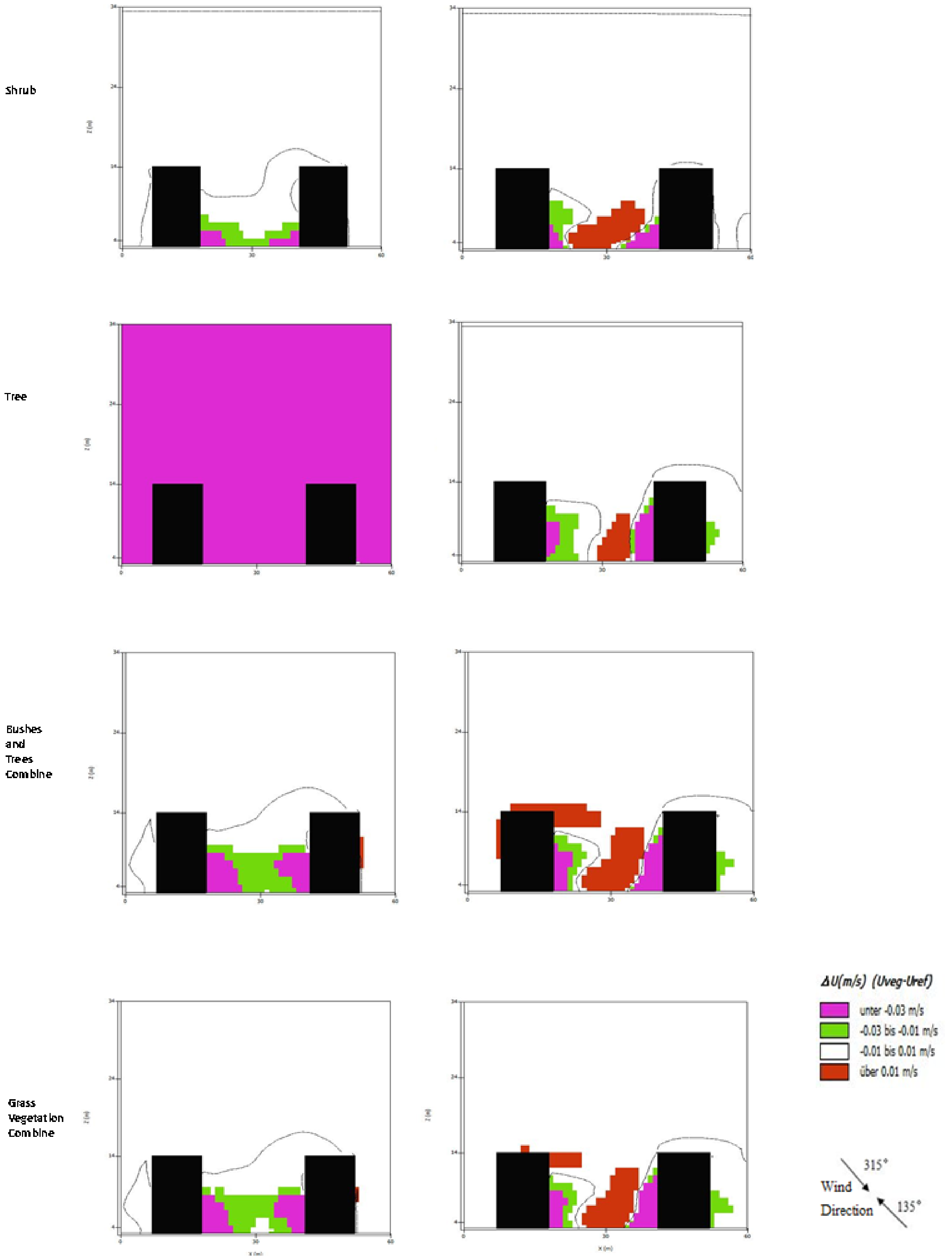

Fig. 6. Influence of vegetation on wind speed in the canyon with aspect ratio is 0.9 for the simulation with wind speed 1 m/s (reference case, Uref; vegetation scenarios, Uveg).

vegetation combine> bushes and trees combine> shrub> tree> no greenery.

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