Chin. Geogra. Sci. 2011 21(4) 465–475
doi: 10.1007/s11769-011-0488-7
www.springerlink.com/content/1002-0063

Urban Green Space Planning Based on Computational Fluid Dynamics Model and Landscape Ecology Principle: A Case Study of Liaoyang City, Northeast China

ZHOU Yuan[1, 2], SHI Tiemao[1, 3], HU Yuanman[1], GAO Chang[1, 2, 3], LIU Miao[1], FU Shilei[3], WANG Shizhe[3]
(*1. State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110164, China; 2. Graduate University of Chinese Academy of Sciences, Beijing 100049, China; 3. School of Architecture and Urban Planning, Shenyang Jianzhu University, Shenyang 110168, China*)

Abstract: As a result of environmental degradation, urban green space has become a key issue for urban sustainable development. This paper takes Liaoyang City in Northeast China as an example to develop green space planning using the computational fluid dynamics (CFD) model, landscape ecological principles and Geographical Information System (GIS). Based on the influencing factors of topography, building density and orientation, Shou Mountain, Longding Mountain and the Taizi River were selected as the urban ventilation paths to promote wind and oxygen circulation. Oxygen concentration around the green spaces gradually decreased with wind speed increase and wind direction change. There were obvious negative correlation relationships between the oxygen dispersion concentration and urban layout factors such as the building plot ratio and building density. Comparison with the field measurements found that there was significant correlation relationship between simulated oxygen concentration and field measurements ($R^2 = 0.6415$, $p < 0.001$), moreover, simulation precision was higher than 92%, which indicated CFD model was effective for urban oxygen concentration simulation. Only less than 10% areas in Liaoyang City proper needed more green space urgently to improve oxygen concentration, mainly concentrated in Baitai and west Wensheng districts. Based on landscape ecology principle, green space planning at different spatial scales were proposed to create a green space network system for Liaoyang City, including features such as green wedges, green belts and parks. Totally, about 2012 ha of green space need to be constructed as oxygen sources and ventilation paths. Compared with the current green space pattern, proposed green space planning could improve oxygen concentration obviously. The CFD model and research results in this paper could provide an effective way and theory support for sustainable development of urban green space.

Keywords: green space; computational fluid dynamics; oxygen dispersion pattern; landscape ecology; Liaoyang City proper

Citation: Zhou Yuan, Shi Tiemao, Hu Yuanman, Gao Chang, Liu Miao, Fu Shilei, Wang Shizhe, 2011. Urban green space planning based on computational fluid dynamics model and landscape ecology principle: A case study of Liaoyang City, Northeast China. *Chinese Geographical Science*, 21(4): 465–475. doi: 10.1007/s11769-011-0488-7

1 Introduction

Urban green spaces, especially parks and forests, are important components of urban environments and provide significant ecosystem services (Bradley, 1995; Lütz and Bastian, 2002). Urban green space can sequester carbon dioxide emissions, produce oxygen, absorb air pollution, and alleviate heat island effects. Zhu *et al.* (2004) suggested that the impact of green space on the environment should be considered as three-dimensional and over different spatial scales. Wind flow in cities is particularly important because it affects natural ventilation as well as green space functions, such as the spatial dispersion of oxygen released from plants. However, the

Received date: 2010-11-24; accepted date: 2011-04-18
Foundation item: Under the auspices of National Key Technology Research and Development Program of China (No. 2008BAJ10B01-01), National Natural Science Foundation of China (No. 40801069)
Corresponding author: SHI Tiemao. E-mail: tiemaos@sjzu.edu.cn

impact of the urban wind field on green space planning has been ignored, particularly in the early design stages (Alcoforado *et al*., 2009). Numerous experimental and numerical studies have been conducted to analyze the urban climate; however, urban green space planning that incorporates climate predictions requires further development. Using computer simulations, three-dimensional computational fluid dynamics (CFD) model can help to study the urban climate and the impact of green space on the environment.

The CFD model has been widely used in engineering flow analysis, building structure design, urban wind flow prediction, and air pollution dispersion at the neighborhood and city scale by applying computer-based numerical methods (Murakami, 2006; Blocken *et al*., 2008). The CFD model comprises a set of physical models that attempt to closely match the real urban geometry and simulate the air flow around buildings and streets (Wong *et al*., 2010). Numerical simulations coupled with CFD model of a complex urban area have been used to investigate the urban thermal environment, air pollutant dispersion and urban wind environment (Robitu *et al*., 2006; Huang *et al*., 2008). Unlike other methods, the CFD model can provide results of the flow features at every point in space simultaneously (Blocken *et al*., 2008). Higher oxygen concentration can be found in areas with plants compared with areas without plants. The amount of oxygen released by plants in urban green space has been calculated in many studies (Uy and Nakagoshi, 2008); however, little attention has been paid to make predictions by combining CFD model with a wind flow pattern. Using CFD model to predict oxygen concentration can be helpful to identify urban areas that are sensitive to factors such as air quality. The CFD model can also be used to analyze and optimize the effectiveness of green space structure planning.

Green space structure is the distribution of green space in terms of patch size, shape and arrangement. Results in some studies have shown that urban green space is rarely uniformly distributed within a town or city (Barbosa *et al*., 2007) and the location of green space is not usually decided according to a scientific rationale (Oke *et al*., 1991). Rapid urbanization accompanied by the marked rise of human population has resulted in the loss of green space, particularly of corridors that connect different patches of green space (McConnachie and Shackleton, 2010). China's urban population in 2001 accounted for 37.7% of its total population, and this proportion may reach 75% by 2050 (Chinese Mayor′s Association, 2002). It means that the remaining urban green spaces are increasingly encroached upon and becoming further fragmented (Jongman, 2008). This not only influences economic sustainability, but also leads to environmental degradation. Recognition of the importance of green space in urban ecosystems has led to considerable work on urban green space planning to improve the urban environment and enhance quality of life (Li *et al*., 2005; Zhou and Wang, 2011). Gilbert (1989) suggested that factors such as size, shape, diversity, and distribution of green spaces within a city as well as individual green spaces specific designed determine their ecological functions. Thus, simply increasing the amount of green space may not be sufficient to increase the provision of ecosystem services. However, there is no general agreement on the desirable planning criteria of urban green space. A scientific basis for the planning of green space in terms of vegetation type, patch structure, spatial pattern and other aspects is necessary to ensure urban green space provide ecosystem services at different spatial scales. This goal could be achieved by applying landscape ecological principle, and other planning methods, as we used in the present study.

The main purpose of this study was to use CFD model (Airpak 2.1.10), landscape ecological principle, and Geographical Information System (GIS) to construct a comprehensive framework for urban green space planning through: 1) identifying urban ventilation paths based on topography, building density and orientation; 2) quantifying spatial dispersion pattern of oxygen concentration released from urban plants under wind flow patterns; 3) analyzing the relationship between oxygen concentration and urban population and identifying suitable sites for green spaces; and 4) proposing a series of green space planning strategies and analyzing the rationality. Results of this paper could provide an effective way and scientific guidance for urban green space planning.

2 Study Area

Liaoyang City (40°42′19″–41°36′32″N, 122°35′04″–123°41′00″E) is located in the northeast of China. It has a temperate climate with an average annual temperature of

8.4℃ and precipitation of 700–800 mm. The southeast wind with a speed of 2.9 m/s prevails in summer. Liaoyang has a variable topography which comprises mountains in the southeast, and the plain in the northwest where the elevation is below 50 m above sea level. The predominant vegetation is deciduous broadleaf forest and mixed coniferous and broadleaf forest (Fig. 1). It is characterized by high population density, high building density and low greening rate. Liaoyang has a total area of 309 km^2 and population of approximately 629 625, with an average population density of 2037 person/km^2 in the city proper, based on data obtained from the Liaoyang Municipal Statistical Bureau (2008). The city proper has around 3194 ha of green space. There are four administrative districts: Baita, Wensheng, Hongwei and Taizi River. Baita and Wensheng have high density population because they are centers of the old town, and have many of main buildings of the city. Hongwei and Taizi River are the main industrial areas, and the population density is relatively lower than that of Baita and Wensheng. The Taizi River, an important river in the northeast of China, flows through the downtown area of the city from the southeast to the northwest.

3 Data and Method

3.1 Data and processing

A QuickBird image in 2009 was used to produce urban land use, building density and green space maps through manual interpretation based on GIS and ground truthing methods. Aerial photographs (1∶10 000) from 2005 and a topographic map (1∶10 000) from 1999 were used to rectify the image. Meteorological data were collected from Liaoyang Meteorological Station from 1992 to 2009. Field measurements of oxygen concentration were conducted on August 3–8, 2009 with a total of 30 measurement points. Measurement points 1–10 were in the residential area, points 11–20 were in the green spaces, and points 20–30 were on a sidewalk of southeast-northwest road. Measurements were taken at the height of 1.5 m above the ground. The oxygen concentration of the samples was measured using an Austenitic gas analyzer. Population data provided by the Liaoyang Municipal Statistical Bureau (2008) was used to produce a population density map, with streets or township as the statistical unit based on a GIS spatial analysis function. 200 green space samples with a size of 20 m × 20 m in Liaoyang City proper were selected to acquire vegetation data in August, 2009 by field investigation method for the tree information such as the name, height, crown width and diameter at breast height.

3.2 Ventilation path delimitation

To improve air quality and promote oxygen dispersion, wind circulation should not be restricted. The main factors influencing wind circulation are urban physical characteristics, particularly topography and building density; these were incorporated into the ventilation

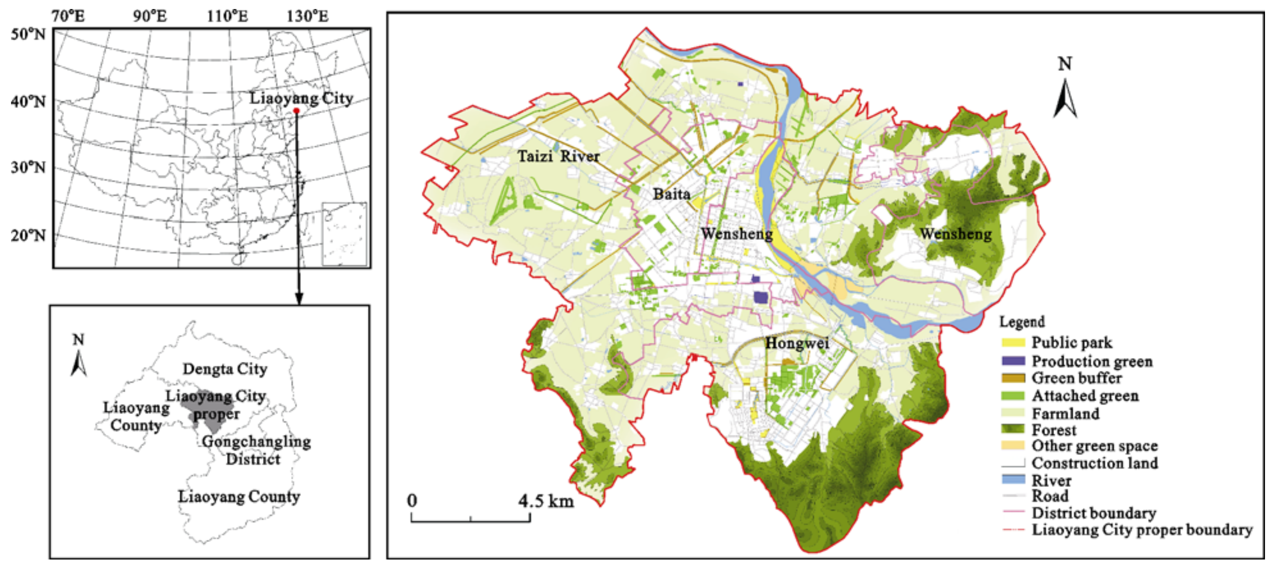


Fig. 1 Location and urban green space types in Liaoyang City proper

map of this study to characterize the urban wind environment. A Digital Terrain Model (DTM) was used to analyze the topography. After the identification of the major morphological units, the valley beds and the mountain tops were delimited by subtracting the values of the absolute altitudes. Top areas are nearly always well ventilated. Building density was divided into five main groups (Alcoforado *et al*., 2009): 1) very high density, where buildings occupy approximately 50% of the total area; 2) high density, where buildings cover between 30%–50% of the total area; 3) medium density, where buildings cover between 15%–30% of the total area; 4) low density, where buildings cover less than 15% of the total area; 5) very low density, which are areas that mostly comprise green space.

3.3 Computational fluid dynamics model

The CFD model was applied to research the air movement and determine the oxygen distribution at the city scale. In this paper, CFD model was used to simulate three dimensional dispersion pattern of oxygen concentration in Liaoyang City proper. We assumed that the city was in the flow field, dominated by atmospheric motion, mainly through wind movement. Therefore, digital urban modules in a wind tunnel simulation were established to manipulate weather and geographical parameters according boundary conditions. The simulation steps of CFD model are are as follows (Huang *et al*., 2008).

3.3.1 Urban boundary and initial conditions setting

For the CFD model simulation, a large scale three-dimensional urban geometric room was built, with a size of 30 000 × 30 000 × 400 m^3. Variables such as wind velocity, solar location and temperature were set as the initial conditions of the room in the CFD model. In corresponding locations of the room, inlet and outlet openings were established to simulate the urban wind direction according to the climatic conditions. The wind velocity was expressed in the form of power law wind profile, which is expressed as (Liu *et al*., 2010):

$$\frac{U}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^{\alpha} \tag{1}$$

where U is the mean wind velocity at height Z (m/s); U_{ref} is the mean wind velocity at the reference height Z_{ref} (m/s); α is the power law exponent, which, in general, is taken to be 0.2–0.5 in urban areas. Because this study was set in urban area where buildings were relatively dense, we selected a value of 0.4 in the simulation. The wind speed setting was based on data from the Liaoyang Meteorological Station collected during 1992–2009. Since the mean wind speed at the meteorological stations was recorded at a height of 10 m above the ground, this data was corrected using the power law function to estimate the wind speed at a height of 1.5 m above the ground.

3.3.2 Urban module establishment

In the simulation, we built urban modules including urban buildings, green spaces and water based on the urban underlying surface. Building urban modules requires digitizing complex urban entities. Urban buildings were modeled as barriers that changed wind speed and direction. Green spaces were modeled as source terms and considered as semi-transparent mediums in the model, and oxygen concentration released from green spaces needed to be calculated as the simulation parameters of green space modules. Based on the green space field investigation data, oxygen release capability per leaf area of the main tree species (Song, 2006) and remote sensing images, mean oxygen concentration released from different green spaces during the daytime in August, 2009 was calculated by using a regression model for urban tree leaf area (Nowak, 1994). For convenience during model simulation, urban green space and building classification are important. Different types of green space and urban building modules in combination with building density, height and plot ratio, and the urban ventilation path distribution were integrated and simplified. Buildings of similar heights that were close to each other were grouped together and regarded as a single building.

3.3.3 CFD simulation process

The first step was to calculate the grid of digital model, which affects the calculation accuracy significantly. The finer the grid, the higher the accuracy; however, the calculation speed is greatly reduced. Appropriate accuracy of grid is necessary for large scale urban. Grid size is established based on the important classes and structure of digital modules, if necessary, which meant increasing local mesh density.

The second step was model computation. The air flow field has characteristics of non-compression, turbulence and viscosity, and it is often non-isothermal. The basic governing equations of non-compressed, non-isothermal flow field are as follows (Robitu *et al*., 2006; Li, 2008).

$$\frac{\partial(u_i)}{\partial x_i}=0 \tag{2}$$

$$\frac{\mathrm{d}u}{\mathrm{d}t}=-\frac{1}{\rho}\frac{\partial P}{\partial xj}+\frac{\partial\left(\nu\frac{\partial(u_i)}{\partial x_j}\right)}{\partial xj}-g_i\beta\Delta\theta \tag{3}$$

$$\frac{\mathrm{d}\theta}{\mathrm{d}t}=\frac{\partial\left(\alpha\frac{\partial\theta}{\partial x_j}\right)}{\partial xj} \tag{4}$$

$$\frac{\partial(C_i)}{\partial t}+\frac{\partial(u_i)(C_i)}{\partial xi}=\frac{\partial}{\partial xi}\left(D\frac{\partial(C_i)}{\partial x_i}-(u_i'C_i')\right) \tag{5}$$

where, u_i is the air instantaneous velocity of three components i (m/s); x_i is the spatial coordinate (m); t is the time (s); ρ is the air density (kg/m^3); P is the instantaneous pressure (N/m^2); ν is the molecular motion viscosity (m^2/s); g_i is the gravitational acceleration (m/s^2); β is the coefficient of volumetric expansion (1/℃); θ is the transient temperature (℃); α is the molecular thermal diffusion coefficient (m^2/s); D is the diffusion velocity (m^2/s); C_i is the mean mass fraction of oxygen concentration.

The last step was model convergence, which required repeated calculation for each setting equation. In fluid dynamics, the calculation is complete when the outcome of interest is stable or considered to be in a range, this process is the convergence. Convergence and adjustment of the parameters were always considered during our simulations.

4 Results and Analyses

4.1 Urban ventilation path construction

Ventilation paths are important for wind circulation and oxygen diffusion towards the city core. Ventilation paths were delimited based on a combination of three main factors: topography (the main valley beds and mountain tops), building density (Fig. 2) (low density axes) and orientation (along a roughly southeast direction). In Liaoyang City proper, the tops of Shou Mountain and Longding Mountain in the southeast of the city, where vegetation coverage is 34%, are often regarded as oxygen sources and ventilation paths. Ventilation along the valley beds is unrestricted. The Taizi River, along a southeast direction, provides the best ventilation path. The urban ventilation paths can be seen in Fig. 3. To ensure adequate ventilation, the following guidelines should be adhered to: 1) limit urban developments, especially tall buildings, with a southeast orientation; 2) avoid increasing building density, and maintain the height/width ratio less than 1; 3) ensure that green space along the low building density axes should not form dense windbreaks (Alcoforado *et al*., 2009). Based on the analyses mentioned above, urban ventilation path were constructed (Fig. 3).

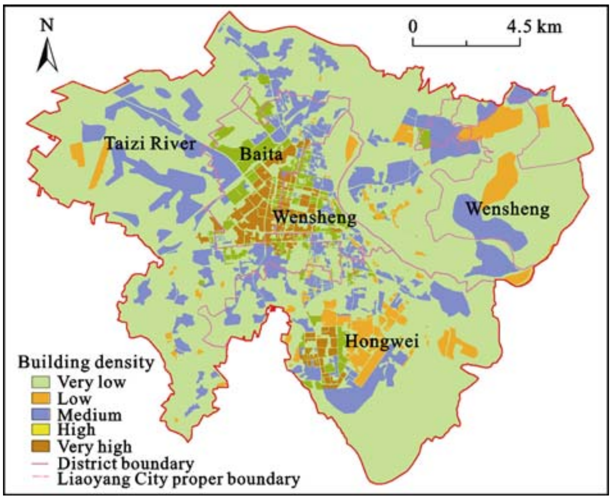


Fig. 2 Building density map of Liaoyang City proper

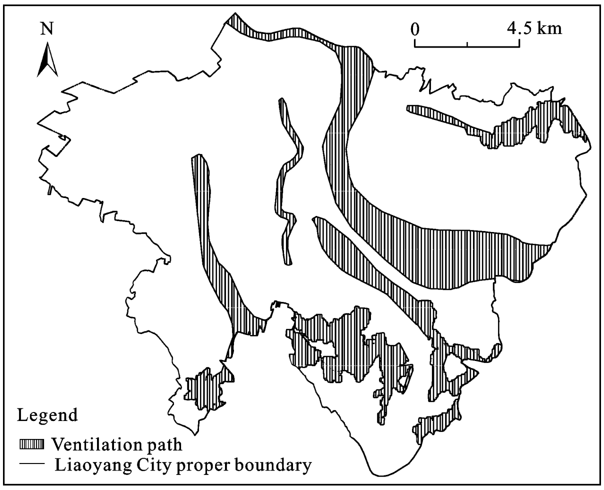


Fig. 3 Construction of urban ventilation paths

4.2 Oxygen dispersion pattern simulation

4.2.1 Oxygen horizontal dispersion pattern

Figure 4a presents the oxygen horizontal dispersion concentration at a height of 1.5 m above the ground. It indicates that oxygen was first emitted from vegetation in the green space, and then dispersed into the air. Oxygen concentration gradually decreased in the direction of urban wind field. Oxygen concentration was effected by urban underlying surface. In Taizi River and Hongwei districts, there are more natural woodlands and farmlands, and relatively lower population density and building plot ratio, which resulted in high oxygen dispersion concentration. In Wensheng and Baita, where had relatively higher population density and building plot ratio, more concentrated building distribution and fewer green spaces, the oxygen dispersion concentration was lower. It suggests that it is important to consider population distribution when determining the areas that require more urban green spaces to increase oxygen concentration.

4.2.2 Oxygen vertical dispersion pattern

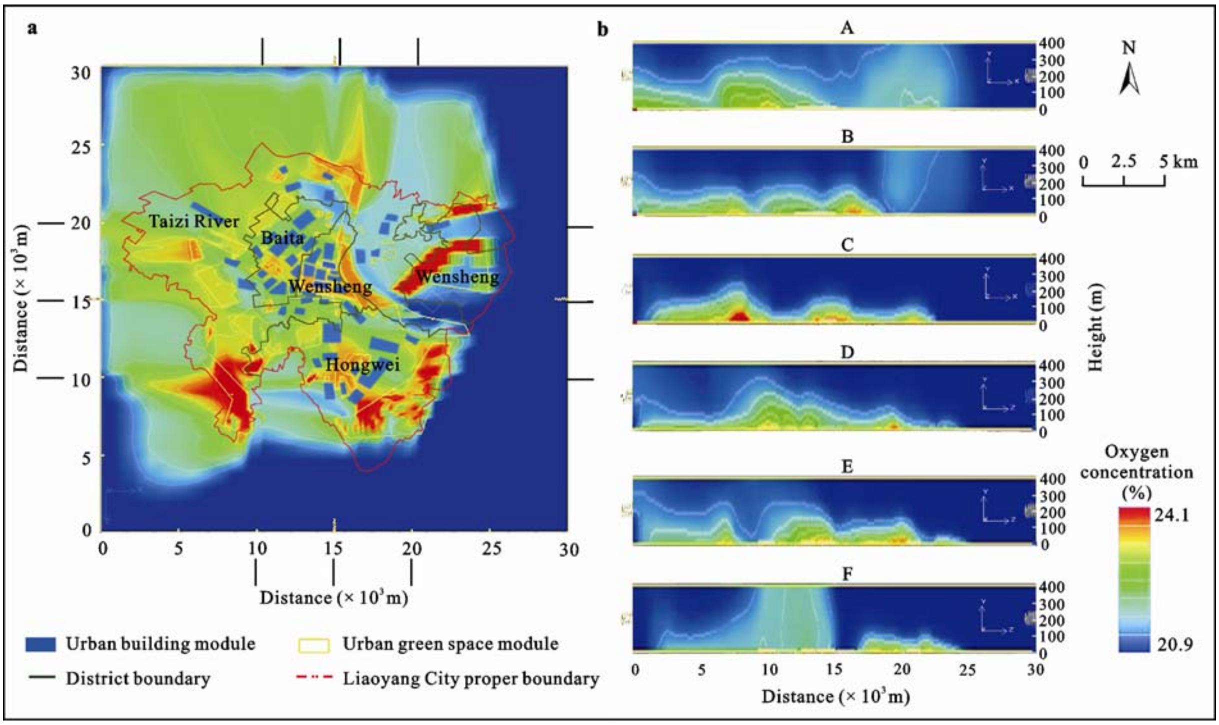
We chose six typical green sections to present the vertical dispersion of oxygen concentration at different heights above the ground (Fig. 4b). From the different sections, it is clear that oxygen spreads from the center of green space. At the height of 0–100 m, the oxygen concentration decreased with height increasing, and the dispersion range also was limited. Oxygen nearly did not disperse above a height of about 300 m. Based on analysis of the vertical dispersion map and urban land use types, the factors that affect the oxygen vertical dispersion concentration include green space structure, layout and height of urban building, and wind environment.

4.2.3 Validation

Since extensive validations have been conducted in previous studies on the wind field and temperature field (Takahashi *et al*., 2004; Huang *et al*., 2008), the focus of this study is mainly on the validation of oxygen concentration. Figure 5a shows that the changing trend is nearly the same for simulation results and field measurements of oxygen concentration simulation. Moreover, there exists significant correlation relationship between them ($y = 0.8304x + 4.0540$; $R^2 = 0.6415$, $p < 0.001$) (Fig. 5b). The mean relative error between the simulated oxygen concentration and the values measured was less than 8%, that is, the simulation precision was higher than 92%. The validation results show that simulated oxygen concentration using CFD model in this paper is accuracy and credible, and the CFD model is useful for complex urban oxygen concentration simulation.

4.3 Suitability for green space construction

Oxygen is mainly consumed by the burning of fuel and



—— represents the tangent line; A, B, C, D, E, F are vertical sections

Fig. 4 Simulated oxygen horizontal (a) and vertical (b) dispersion pattern in Liaoyang City proper natural gas, and respiration and biochemical consumption; however, in this study, only human respiration was considered. Spatial distribution of mean population density (Fig. 6) and simulated oxygen concentration data of different land use types were acquired by using spatial analysis of Zonal Summary in GIS. The relationship between oxygen concentration and population density is presented in Fig. 7. The results shows that oxygen dispersion concentration is significantly correlated to urban population density (y = –0.4356x + 23.2040; $R^2 = 0.6176$, $p < 0.001$).

Using GIS, an overlay map of oxygen concentration, population density and land use was produced to show the areas that need more green space (Fig. 8). Very highly suitable areas that most need to increase green space only account for 1.6% of total area, while it is 7.8% for the highly suitable areas, 23.4% for moderately suitable areas, 43.5% for low suitable areas, and 23.6% for very low suitable areas. The results demonstrate that oxygen concentration in most areas of Liaoyang City proper can meet the need of human, and only less than 10% areas need more green space urgently. Among all districts, the areas that most need green space are mainly concentrated in Baita and west Wensheng districts, which are the centers of the old town, because of their high population density and uneven distribution of green spaces. In districts of Taizi River, eastern Wensheng and Hongwei, the suitability for

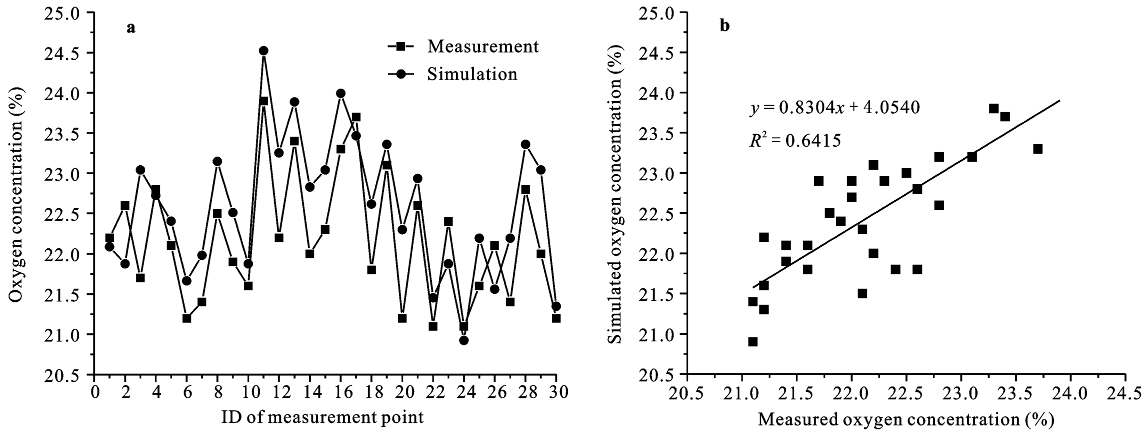


Fig. 5 Comparisons of changing trend (a) and relationship (b) between simulation results and field measurements of oxygen concentration

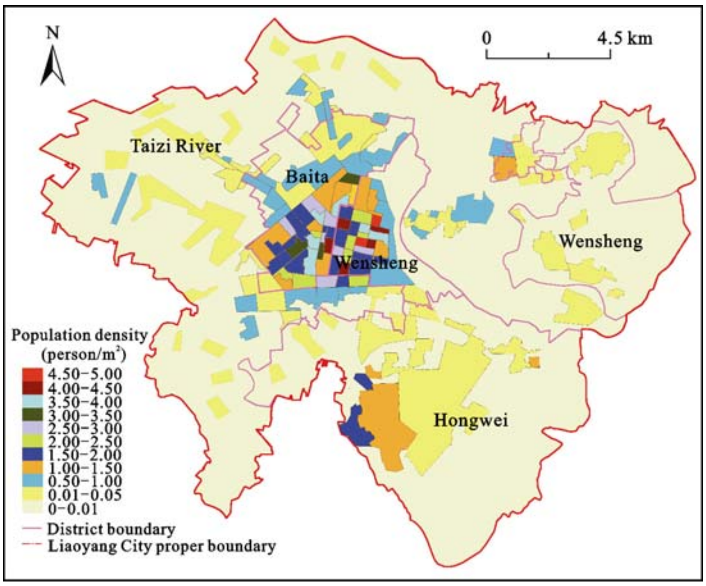


Fig. 6 Population density map of Liaoyang City proper

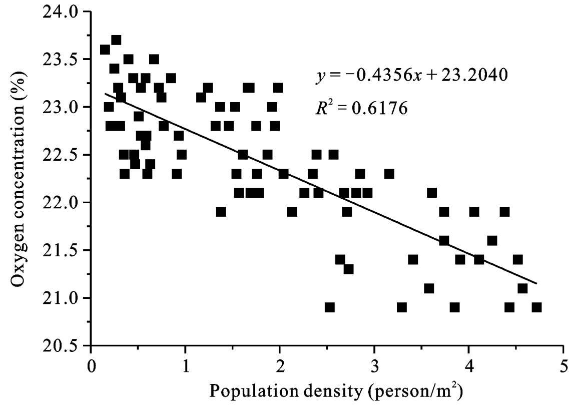


Fig. 7 Linear relationship between oxygen concentration and population density in study area

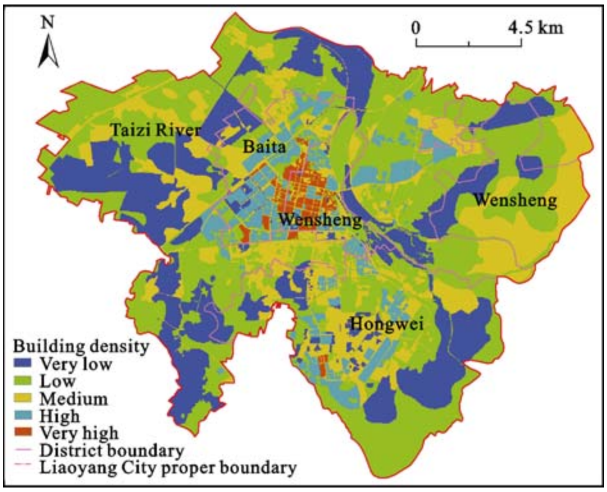


Fig. 8 Distribution of suitability of green space construction in Liaoyang City proper

green space construction is lower because more oxygen is released by plants in the surrounding mountains.

4.4 Green space planning

Landscape ecology principles can be used to provide a theoretical basis for landscape and urban planning. Based on the analysis results mentioned above, the urban ventilation paths and the suitable sites for more green spaces were identified. Therefore, it is important to apply landscape ecology principles to improving the existing green spaces structure at different spatial scales.

At a regional scale, the mountains in Liaoyang City cover an area of approximately 100 km^2 and have a length of 40 km from southwest to northeast. In summer, the oxygen released from the mountainous vegetations will disperse into the air because of the prevailing southeast wind. The Taizi River and surrounding green vegetation will be important ventilation paths directing wind into the city in summer. Vegetation coverage of the mountains should be improved, and additional urban ventilation paths should be constructed to direct the oxygen released by the vegetation. Based on the above analysis, we propose seven green wedges which mostly include grass and low vegetation, and one large green ring composed of parks, forests, farmlands and rivers, to connect the outer and inner green space and create an ecological network (Fig. 9). The wedges in the southeast of the city can act as both ventilation paths and oxygen sources, while the other green wedges act as ecological corridors. This type of green structure planning could ′bring nature into the city′.

At the city scale, the current green space is mainly the public parks, urban forests and agricultural land in the City proper. To provide ventilation paths and oxygen sources, keep the continuity and connectivity of green patches, several green belts and a small green ring, which form an integrated ecological network in the city proper, are proposed based on the landscape ecology principles and the oxygen dispersion pattern. Park nodes, green belts and green rings can together form a diversified urban landscape structure (Fig. 9). Almost all industrial zones in Liaoyang are concentrated in the Hongwei district, where air pollution is a serious problem. Constructing a green belt between Hongwei and other districts is necessary, not only provide an oxygen source but also to improve air quality.

At the neighborhood scale, based on the centralized and decentralized ecological principle, some green space within the city proper should be expanded to act as oxygen sources when old buildings are demolished. Green spaces, green roads and riparian buffers should be created following the landscape ecology principle and ventilation path guidelines. Green space provides residents with an opportunity to contact with nature as well as providing fresh oxygen. Green infrastructure can be incorporated in various ways including rooftop greening, balcony greening and wall greening. Moreover, there should be a focus on the structure of green space to enhance the ecological benefits. For instance, a forest should include a main tree canopy and an underlayer of shrubs and herbs for community stability and the potential for the provision of more ecosystem services (Li *et al.*, 2005). Green roads are an important component of

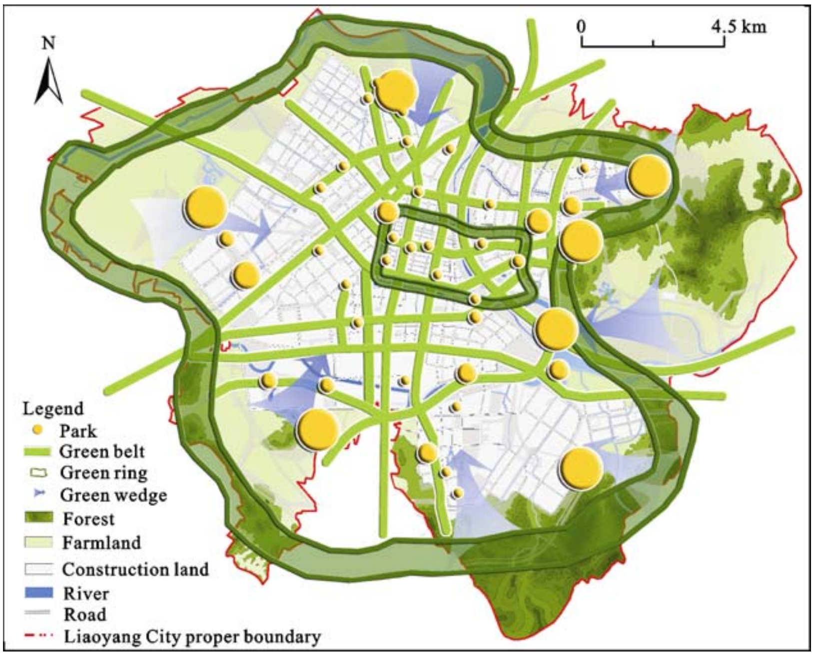


Fig. 9 Proposed green space planning in Liaoyang City proper

green space network in urban, which should be developed when constructing new roads or reconstructing old roads. Both sides of roads are suitable for planting dense green belts to segregate traffic and living space, and the greening can be 20–30 m wide. If the road does act as a ventilation path, green space behind the dense green belt should be planted with sparse and low vegetation. Riparian buffers acting as ventilation paths and oxygen sources also play an important role in connecting the green space network. Rivers, such as the moat within the city, are also natural corridors that link urban green space areas.

4.5 Rationality analysis of green space planning

Figure 10 shows the three-dimensional spatial dispersion pattern of oxygen concentration in proposed green space planning. In this study, we increased the green area by about 2012 ha in the locations identified as suitable ones based on the planning of urban green space structure and land use types. The proposed green space includes parks, green wedges and green belts and are mainly concentrated in Baita, Wensheng and in the urban fringe. It is clear that the oxygen coverage of the planning scenario is much greater than that of the current situation. Compared with the current oxygen concentration dispersion pattern (Fig. 4), in horizontal or vertical space, the spatial dispersion range of oxygen concentration obviously increased due to the increase of green areas in appropriate locations. The impact of greenery increase is very significant in the urban areas with limited green space. Therefore, proposed green space planning is rational and effective in this paper.

5 Conclusions

The integrated application of CFD model, landscape ecology theory and GIS technology is an innovative approach for green space planning. In this study, we built a comprehensive method framework for urban green space planning and proposed an effective and rational green space planning pattern.

To promote wind and oxygen circulation, the tops of Shou Mountain and Longding Mountain, and the Taizi River were selected as the urban ventilation paths based on the main factors of topography, building density and orientation. Oxygen concentration around the green spaces gradually decreased with wind speed increase and wind direction change. Oxygen horizontal dispersion concentration was influenced by population density, and urban layout factors such as building plot ratio and building density. The factors affecting the oxygen vertical dispersion concentration include green space structure, layout and height of urban building, and wind environment. Simulated oxygen concentration was sig-

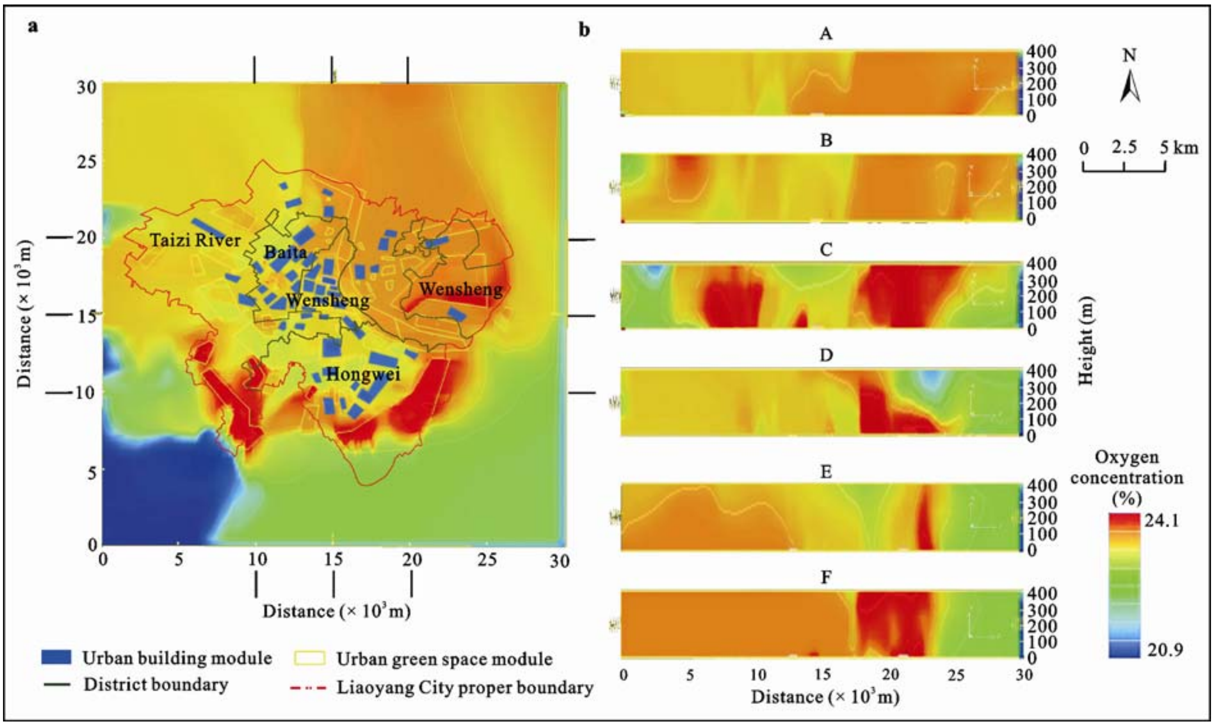


Fig. 10 Proposed oxygen horizontal (a) and vertical (b) dispersion pattern for Liaoyang City proper

nificant correlated with field measurements ($R^2 = 0.6415$, $p < 0.001$), and simulation precision was higher than 92%. Suitability analysis indicated that oxygen concentration in most areas of Liaoyang City proper can meet the need of human, and only less than 10% areas needed more green space urgently, mainly concentrated in Baitai and west Wensheng districts. Combined with landscape ecology principle, we proposed that Liaoyang City should develop additional green area of about 2012 ha to act as oxygen sources and ventilation paths. A conceptual green space planning was proposed at the regional, city, and neighborhood scales. In the proposed plan for the green structure of Liaoyang, at the regional scale, there should be seven green wedges and a green ring to 'bring nature into the city' and enhance the connectivity of the green network. At the city scale, several green belts and a small green ring that form a network was proposed to ensure the continuity and connectivity of green patches. At the neighborhood scale, green areas, green roads and riparian buffer green space within the city proper should connect with existing isolated residential green space and small green spaces to ensure sufficient oxygen released from vegetation. Validation results showed that proposed green space planning can improve the provision of ecosystem services of urban green space through increasing green space at appropriate areas. The CFD model and the integrated method presented in this paper do have implications for the development of urban green space structure in order to maintain sustainable environment.

Three-dimensional CFD model simulation method discussed in this paper are less used in real green space planning projects. Therefore, we should strengthen the development of urban environment digital systems for green space planning projects. The main focus of this study was oxygen diffusion pattern at the city scale, but there are still many issues, such as the effect of green space layout at the micro scale on oxygen diffusion, which are needed to be studied further. Additionally, improvements of CFD simulation accuracy, air pollutant spatial dispersion and heat island effects, are needed to be further researched to guide urban green space planning.

Acknowledgments

Authors are grateful to all the members who conducted field surveys in the Liaoyang City. The authors give special thanks to Zhang Peihong and Zhang Xinchun of Shenyang Jianzhu University for their continuous support and sincere help.

References

Alcoforado M J, Andrade H, Lopes A *et al*., 2009. Application of climatic guidelines to urban planning: The example of Lisbon (Portugal). *Landscape and Urban Planning*, 90(1–2): 56–65. doi: 10.1016/j.landurbplan.2008.10.006

Barbosa O, Tratalos J A, Armsworth P R *et al*., 2007. Who benefits from access to green space? A case study from Sheffield, UK. *Landscape and Urban Planning*, 83(2–3): 187–195. doi: 10.1016/j.landurbplan.2007.04.004

Blocken B, Stathopoulos T, Saathoff P *et al*., 2008. Numerical evaluation of pollutant dispersion in the built environment: Comparisons between models and experiments. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(10–11): 1817–1831. doi: 10.1016/ j.jweia.2008.02.049

Bradley G A, 1995. *Urban Forestry Landscapes*: *Integrating Multidisciplinary Perspectives*. Seattle: University of Washington Press.

Chinese Mayor's Association, 2002. *The Report of 2001–2002 Chinese Urban Development*. Beijing: Xiyuan Publishing House. (in Chinese)

Gilbert O L, 1989. *The Ecology of Urban Habitat*. London: Chapman& Hall.

Huang H, Ooka R, Chen H *et al*., 2008. CFD analysis on traffic-induced air pollutant dispersion under non–isothermal condition in a complex urban area in winter. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(10–11): 1774–1788. doi: 10.1016/ j.jweia. 2008.02.010

Jongman R H G, 2008. Ecological networks are an issue for all of us. *Journal of Landscape Ecology*, 1(1): 7–13.

Li F, Wang R S, Panlussen J *et al*., 2005. Comprehensive concept planning of urban greening based on ecological principles: A case study in Beijing, China. *Landscape and Urban Planning*, 72(4): 325–336. doi: 10.1016/j.landurbplan.2004.04.002

Li Kun, 2008. *City Heat Environment Research Based on Remote Sensing and CFD Simulation—A Case Study of Wuhan City in Summer*. Wuhan: Huazhong University. (in Chinese)

Liaoyang Municipal Statistical Bureau, 2008. *Statistical Yearbook of Liaoyang Ctiy*. Beijing: China Statistics Press. (in Chinese)

Liu X P, Niu J L, Kwok K C S *et al*., 2010. Investigation of indoor air pollutant dispersion and cross-contamination around a typical high-rise residential building: Wind tunnel tests. *Building and Environment*, 45(8): 1769–1778. doi: 10.1016/j.buildenv.2010.02.003

Lütz M, Bastian O, 2002. Implementation of landscape planning and nature conservation in the agricultural landscape—A case study from Saxony. *Agriculture, Ecosystems and Environment*, 92(2–3): 159–170. doi: 10.1016/S0167-8809(01)00300-0

McConnachie M M, Shackleton M C, 2010. Public green space inequality in small towns in South Africa. *Habitat International*, 34(2): 244–248. doi: 10.1016/j.habitatint.2009.09.009

Murakami S, 2006. Environmental design of outdoor climate based on CFD. *Fluid Dynamics Research*, 38(2–3): 108–126. doi: 10. 1016/j.fluiddyn.2004.10.006

Nowak D J, 1994. Understanding the structure of urban forests. *Journal of Forestry*, 92(10): 42–46.

Oke T R, Johnson G T, Steyn D G *et al*., 1991. Simulation of surface urban heat islands under 'ideal' conditions at night. Part 2: Diagnosis of causation. *Boundary-Layer Meteorology*, 56(4): 339–358. doi: 10.1007/BF00119211

Robitu M, Musy M, Inard C *et al*., 2006. Modeling the influence of vegetation and water pond on urban microclimate. *Solar Energy*, 80(4): 435–447. doi: 10.1016/j.solener.2005.06.015

Song Li, 2005. Species selection of urban forest in Shenyang. Shenyang: Institute of Applied Ecology, Chinese Academy of Sciences. (in Chinese)

Takahashi K, Yoshida H, Tanaka Y *et al*., 2004. Measurement of thermal environment in Kyoto City and its prediction by CFD simulation. *Energy and Buildings*, 36(8): 771–779. doi: 10.1016/j.enbuild.2004.01.033

Uy P D, Nakagoshi N, 2008. Application of land suitability analysis and landscape ecology to urban greenspace planning in Hanoi, Vietnam. *Urban Forestry and Urban Greening*, 7(1): 25–40. doi: 10.1016/j.ufug.2007.09.002

Wong M S, Nichol J E, To P H *et al*., 2010. A simple method for designation of urban ventilation corridors and its application to urban heat island analysis. *Building and Environment*, 45(8): 1880–1889. doi: 10.1016/j.buildenv.2010.02.019

Zhou X L, Wang Y C, 2011. Spatial-temporal dynamics of urban green space in response to rapid urbanization and greening policies. *Landscape and Urban Planning*, 100(3): 268–277. doi: 10.1016/j.landurbplan.2010.12.013

Zhu Ning, Li Min, Chai Yixin, 2004. Spatial analysis of integrated ecological effects of urban greenland. *Chinese Journal of Urban Forestry*, 2(1): 26–28. (in Chinese)