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The "plant evaluation model" for the assessment of the impact of vegetation on outdoor microclimate in the urban environment

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ABSTRACT

This paper discusses current state-of-the-art features of the "plant evaluation model", a framework which, starting from the representation of vegetation and its effects in microclimate models, defines a number of indices which can be employed for the evaluation of outdoor microclimate in terms of thermal environment and comfort in the urban environment. The key point of taking into account the impact of vegetation on microclimate is to implement appropriate parameterizations of such impact in a microclimate model. The paper, based on a review of literature studies, thus illustrates the basic principle and technical path of the impact assessment model of vegetation on microclimate and introduces related software. The aim is to provide the scientific community with a summary of (i) the current definition of vegetation in models employed for the evaluation of the impact of vegetation on urban outdoor microclimate, (ii) main models and evaluation indices and (iii) main input, output, vegetation-related processes implemented, strengths and weaknesses of those models, with suggested measures for output improvement. This review is not exhaustive but may help the user to select the proper model, which takes into account the effects of vegetation on outdoor urban microclimate, depending on the specific objective.

1. Introduction

In urban areas vegetation can not only improve the aesthetic value, but also reduce the Urban Heat Island (UHI) effect and improve the microclimate [1–3]. It is worth discussing the state-of-the-art features of a so called "evaluation model" of vegetation impact on urban microclimate, which contributes to the ecological function of vegetation in urban areas.

For the assessment of urban microclimate, several models have been proposed in the literature. These models rely on different theoretical foundations. Models based on the same theoretical foundations also have some differences in terms of the parameters employed to take into account the effects of vegetation. There is still a lack of extensive validation and thus it is hard to employ a model as an effective application tool. Besides, coupled with the complexity of the environment at local scale, the model selection and the application of tools is still a big issue for both research and planning purposes. In this context, on the basis of literature review, this paper summarizes the vegetation-related components in commonly used microclimate models to evaluate the impact of vegetation on outdoor microclimate and thermal comfort in the urban environment. The summary follows a typical "plant evaluation model" (Section 2), which is a general simulation framework including vegetation-related aspects described in the next sections. In particular, Section 3 presents the search protocol followed for the review of literature studies employing different microclimate models. By analysing the selected studies, the next sections summarize the different ways commonly employed to represent vegetation (Section 4), the plant modules implemented for taking into account the effects of vegetation (Section 5) and the types of microclimate models (Section 6). Section 7 summarizes the different types of evaluation indices developed and employed for the evaluation of the thermal environment and comfort. A discussion on input/output, strengths and weaknesses of each microclimate model is given in Section 8. Conclusions are given in Section 9.

2. Incorporating vegetation-related components into microclimate models

To help the reader understand how this paper is structured, Fig. 1

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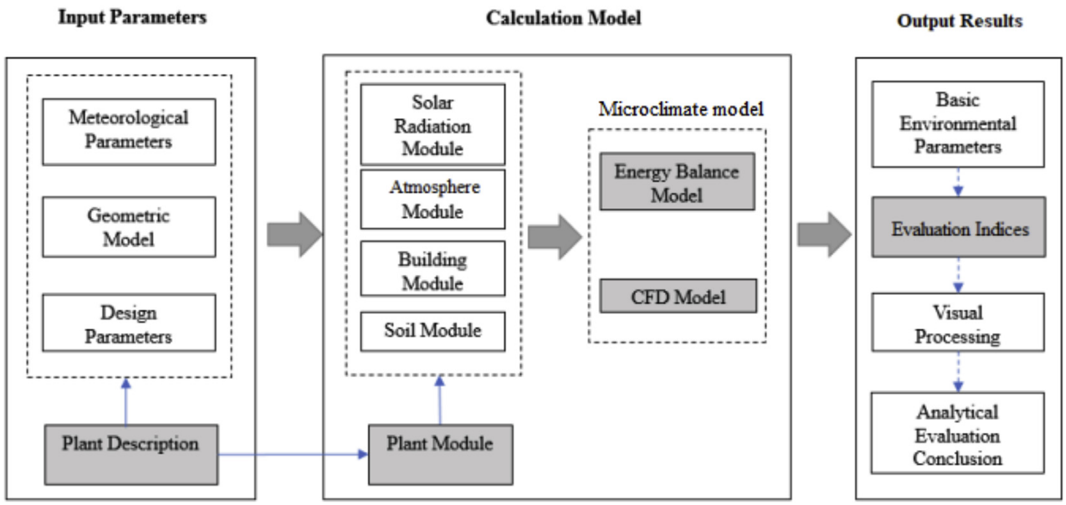

Fig. 1. Framework diagram of the "plant evaluation model" composed of three blocks. For each block the components described in this paper are highlighted in grey.

shows a general simulation framework which includes the vegetation-related components. The framework is composed of three blocks:

- Input Parameters comprise both initial and boundary conditions. They are meteorological, geometric and design parameters. Meteorological parameters are obtained by standard meteorological stations or *ad-hoc* measurements. Geometric model parameters include the main elements of urban geometry, such as buildings and surfaces. Design parameters, like building materials, pollution sources etc., help to describe the boundary of the simulation;
- Calculation Model: usually several modules are implemented in one calculation model, such as solar radiation module, atmosphere module, building module, soil module and so on. These modules are coupled by some parameters;
- Output Results include different basic environment parameters. The visualization is also crucial for post-processing.

Starting from this basic framework, the key point of taking into account the impact of vegetation on microclimate is to translate it into a model language for the corresponding microclimate model, and then use indices for a quantitative evaluation. The impact of vegetation is mainly related to temperature, humidity, radiation, wind and pollutant dispersion through [4]:

- photosynthesis and respiration which lead to the conversion of carbon dioxide (CO_2) and oxygen;
- transpiration which affects the environment temperature and humidity;
- attenuation of the shortwave radiation;
- production of a drag force that affects the airflow distribution and deposition/absorption of air pollutants.

The inclusion of such effects is achieved by adding the "plant description" (described in Section 4) to the Input Parameters and the "plant module" (described in Section 5) to the Calculation Model in order to describe plant characteristics. These descriptive parameters should be able to be coupled with other modules in the microclimate models Energy Balance Model (EBM) and Computational Fluid Dynamic model (CFD) (described in Section 6). To evaluate the thermal condition, it is finally necessary to employ appropriate evaluation indices (described in Section 7). Such framework diagram is referred to as "plant evaluation model". Please note that such framework is not novel, but it is built by adding vegetation-related components to the common framework for simulation.

Specifically, the plant description is the way vegetation is described and represented in a plant module. The plant module concerns the effects of vegetation and is part of the calculation model and thus any simplification of the microscale model affects the coupling with the plant module itself. If the calculation model is too simple, the plant module can only consider some simple effects of vegetation on the environment. Further different calculation models have different ways of coupling with plant modules, and different environmental effects can be simulated.

3. Search protocol

A review of the most used models employed to investigate the effects of vegetation on microclimate in urban environments is performed. The models are divided into two main categories: Energy Balance Models (EBM) and Computational Fluid Dynamics (CFD) models. Please note that here the interest is on the effects of vegetation on urban microclimate, i.e. on temperature, humidity, wind flow and thermal comfort.

The search was conducted in September 2018 through Google Scholar, ScienceDirect, Scopus and only papers written in English were considered. The keywords searched were the following: "*numerical modelling* OR ENVI-met OR FLUENT OR *CFD model* OR *EBM* OR *openFOAM* OR STAR-CCM + OR *evaluation model* OR *RayMan* OR *TEB-Veg* OR *SOLWEIG* OR *PHOENICS* OR *Energy Balance model*" and "*vegetation* OR *green space* OR *park* OR *green roof* OR *tree* OR *green wall* OR *plant* OR *urban forest* OR *urban greening* OR *urban green* OR *city tree* OR *urban comfort*". Articles that respected the quality criteria of credibility, transferability and dependability were chosen [5]. A total of 97 studies, published between 1998 and 2018, has been identified and summarized in Table A1 of Appendix A.

The Energy Balance Models (EBM) include radiation models, such as RayMan [6,7], SOLWEIG (Solar LongWave Environmental Irrandiance Geometry) [8,9], green-CTTC (Cluster Thermal Time Constant) [10], TEB-Veg (Town Energy Balance) [11]. The commonly used CFD models include OpenFOAM (freely available at www.openfoam.com), FLUENT [12] and STAR-CCM+ from Siemens (mdx.plm.automation.siemens.com/star-ccm-plus), PHOENICS with the plant canopy module FOLIAGE [13] and the CFD-based ENVI-met model [14,15]. A detailed discussion of each model is given in Section 6, while input, output, strengths and weaknesses, mostly related to vegetation and thermal comfort parameters, are summarized in Section 8, which may constitute the starting point for the application of the proper microclimate model which takes into account the effects of vegetation depending on the objective of the study.

Fig. 2 shows CFD models are more used than EBMs for the study of

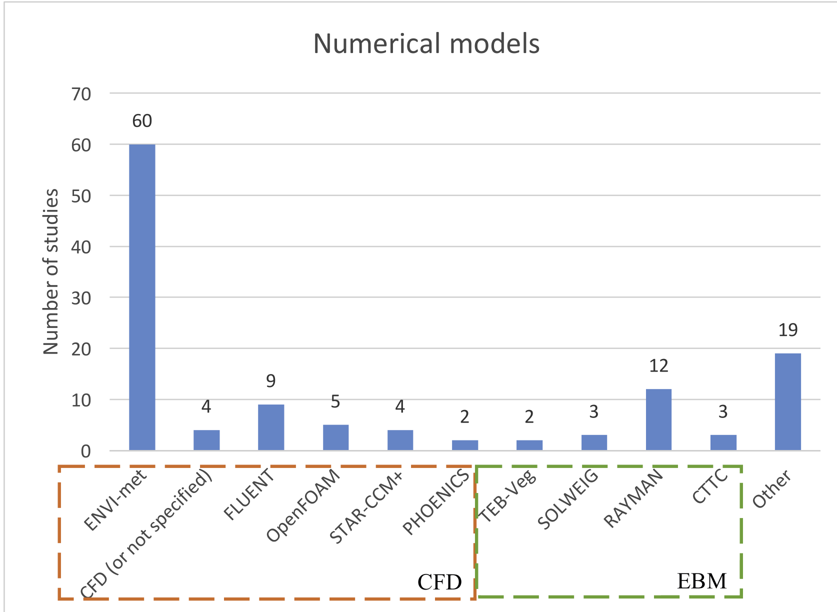

Fig. 2. Microclimate models used to study the effects of vegetation on urban microclimate (on a total of 97 studies). The total number of studies is 123 since 26 studies employed two or more coupled models (see Appendix A).

the effects of vegetation on urban microclimate. In particular, ENVI-met is the model mostly used (60). Few studies used SOLWEIG (3) and RayMan (12). RayMan has been coupled to other models in 11 of the 12 studies. Please note that the total number of studies in the figure is 123 since 26 studies employed two or more coupled models (see Appendix A).

The plant descriptions and modules implemented into the microclimate models are summarized in Table 1 and described in the following sections.

4. Plant description

In large scale models, vegetation is treated as a "vegetation community", and the quantity is usually quantified by vegetation indices such as the normalized difference vegetation index (NDVI), the ratio vegetation index (RVI) and the perpendicular vegetation index (PVI) [16]. In this type of models, the physical properties of plants include geometry, size, roughness and reflectivity. The parameters of different plants or the same plant can be different according to vegetation type, height, density, colour and season. This description is more suitable for the calculation of coupled solar radiation models and relies on empirical parameters in terms of humidity and turbulence [17].

Table 1
Comparison of plant description models and plant modules commonly employed in the analysed microclimate models.

Microclimate model (Section 6)		Plant description (Section 4)	Plant module (Section 5)
EBM	RayMan SOLWEIG CTTC TEB-Veg	Ideal canopy model	Effects on radiation
CFD	PHOENICS, FLUENT, OpenFoam, STAR-CCM +	Ideal canopy model Statistical method Measurement and representation method	Aerodynamic effects
	ENVI-met	Statistical method Geometry method	Effects on radiation Aerodynamic effects Heat and humidity model

In microclimate models, which are the focus of the present paper, plants need to be described in detail so that the simulated inputs and outputs can reflect the actual characteristics as much as possible. As it is difficult to find biophysical models that meet general requirements, the plant canopy model is often used to simplify the problem. The distance, height and diameter of the individual vegetation elements, the depth and shape of the canopy and root, the size, shape, quantity, colour, tissue and spatial distribution of the leaves affect the turbulent vertical exchange of momentum, mass and energy between the canopy and the atmosphere and the absorption of soil moisture. Plants can regulate these fluxes through several mechanisms of change, such as changes in stomatal impedance that control transpiration and CO_2 assimilation, short-term changes in leaf pose, and seasonal variations in colour and density. In the plant canopy model, each individual plant (especially a tree) has a crown that is supported by the trunk or main stem on the ground. The collection of crowns in the cluster is the "plant canopy".

The main solid matter related to water vapour, CO_2, kinetic energy, radiation and heat in plant canopy is leaf. Therefore, the distribution of leaves is the key point of plant description. In order to study these distribution characteristics, leaf area index (LAI, $m^2\ m^{-2}$), that is the total area of plant leaf area per unit projection area, is introduced. It is a dimensionless quantity that can vary with season, age and species [18]. Because it not only directly reflects the growth of plants, but also affects many biological and physical processes of plants, such as photosynthesis, respiration, transpiration, carbon and nitrogen cycle and precipitation interception, it is the most commonly used physical parameter in plant description. A range of LAI values for various plants has been proposed in the literature (e.g. Refs. [19,20]).

There have been proposed five degrees of simplification of plant description in the literature which are summarized below.

4.1. Ideal canopy model

The plant morphology in nature shows some regularity, and the ideal canopy model fixes the proportion of plant morphology directly according to this regularity. In the ideal canopy model most proportions of crowns are identified by an ideal model where generally only the height of the canopy is needed. It is the sum of the height of the crown and the height of the trunk. The plant crown can be simplified and represented as a solid geometry shape and described by some elliptic

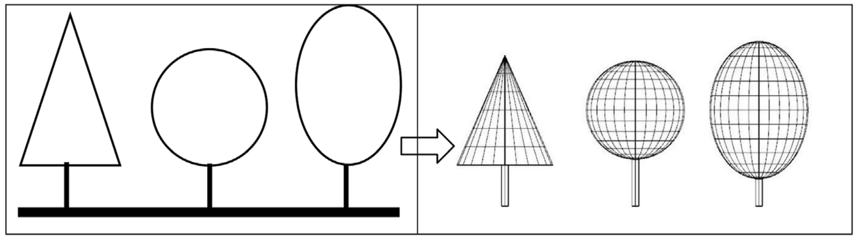

Fig. 3. Plant description by the ideal canopy model.

equations. Because the plant canopy is usually axisymmetric, the single plant crown is simplified as a two-dimensional geometric figure, such as the spherical, oval, conical, which contains plant elements. The ideal canopy model generally can only determine the geometric contour of a plant canopy but cannot show the distribution of leaves. Generally, the plants are only involved in shadow correlation calculation, or as simple geometry in turbulence calculation, which is difficult to correlate with plant growth parameters. The geometry of plants in the model can be obtained by observation, while the approximation error is large, as the ideal empirical equation may be quite different from the actual one. There are some EBM models that use this method, such as the radiation models RayMan and SOLWEIG; in most CFD models users can also use this method to simplify three dimensional plants. The ideal canopy models and the corresponding three-dimensional plants are shown in Fig. 3.

4.2. Statistical method

Statistical method associates the LAI with the plant morphology. Therefore, the plant model has attribute changes at different heights. While the spatial difference within the canopy and the leaf inclination is not considered and the leaf stem structure of plant canopy is stable, hierarchical and homogeneous. Monsi and Saeki [21] first used this method to study the extinction coefficient of vertical layers within the crown based on Beer-Lambert law. If the plant layered LAI in the statistical model is standardized and corrected, then all plant morphologies can be fixed into rectangle. Fig. 4 shows the four parts of plant description by statistical methods, where each part from the left to the right represents the ideal canopy model, the ideal canopy model with horizontal section, the statistical model and the standardized statistical model. This method is suitable for mesh generation in CFD, and it is beneficial to the convergence of turbulence simulation [22]. The FOLIAGE module of the CFD model PHOENICS and the Simple Plant module of the CFD-based ENVI-met model adopt this method.

4.3. Geometry method

Statistical method is an ideal hypothesis for the horizontal homogeneous distribution of leaves. The final shape after standardization is quite different from the actual geometry of individual plant, which may have a great influence on the calculation results of shadow and radiation. To overcome these issues, the geometry method discretizes the space by mesh generation, thus preserving the approximate form of plants. The leaf volume is homogeneous in unit volume and the LAI changes with spatial location. When describing vegetation communities by geometric methods, each plant has its own specific shape and spatial position, which is suitable for describing more complex individual plants or communities (Fig. 5). Because the shape is closer to reality, it is more beneficial to radiation calculation, but it will increase the workload of turbulent computation. In addition, different forms may cause errors in empirical models of turbulence models. The ENVI-met 3D-Plant module adopts it by employing the so-called plant editor Albero.

4.4. Measurement and representation method

This is a method of restoring the true three-dimensional shape of a plant by comparing accurate measurements and modelling. Although the model established by this method is meticulous, it lacks a general description method. The amount of data is large, and the acquisition is difficult, and it is also hard to expand from the individual to the community. In addition, this method pays too much attention to the visual form and ignores the application requirements. Due to the lack of simplification, problems may arise in simulation convergence, and systematic errors may be large. This method has been used in individual turbulence simulation studies combined with wind tunnel tests (see for example [23], as shown in Fig. 6.

4.5. L-system method

There are similar forms in the whole and parts of the plant, such as the simple recursive rule often followed by plant-generated branching shapes and leaf patterns. In fact, there are widespread self-similar phenomena in nature. Mandelbrot [24] represented the phenomenon of self-similarity into fractals - it is hailed as the geometry of nature, solving the problem of natural form descriptions that were not good at geometry in the past. In 1968, the biologist Lindenmayer made a mathematical summary and abstraction of the plant growth process. He

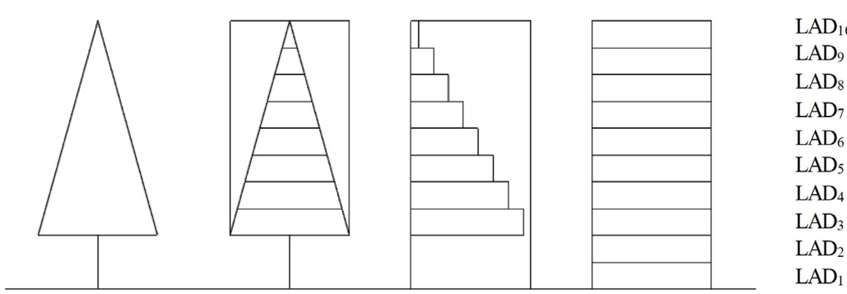

Fig. 4. Plant description by statistical method: the ideal canopy model, the ideal canopy model with horizontal section, the statistical model and the standardized statistical model through vertical distribution of leaf area density (LAD, $m^2\ m^{-3}$) (from left to right).

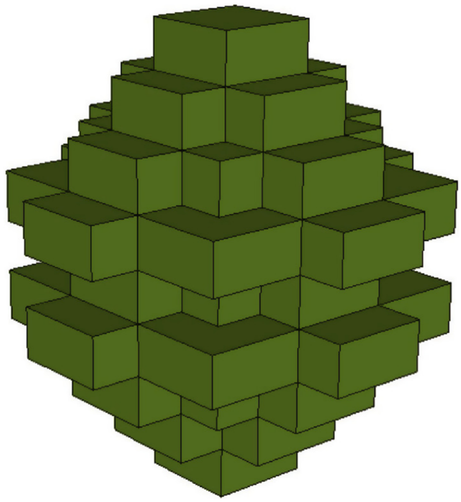

Fig. 5. Plant description by Geometry method, where each cell in the model represents a specific LAD value. The shape of the whole model is closer to the real tree and sparse changes in space.

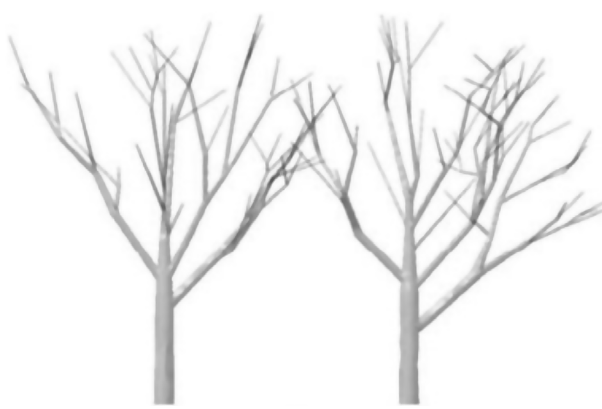

Fig. 6. The three-dimensional shape of the plant used by the measurement and representation method (from Ref. [23] ©Elsevier, reprinted with permission of Elsevier).

proposed the String rewriting system, which is called L-system [25]. L-system considers the branching structure of plants as a regular topological structure, determines the initial state of the plant, describes the rules and, after a limited number of iterations, can produce complex fractal patterns similar to natural plants. The rules for change control in the earliest L-system (defined as 0 L-system) are deterministic, and only regular fractal patterns can be generated. With the development of L-system functions, random L-system, parameter L-system, context-sensitive L-system and open L-system appear. Now computers have been able to simulate the complex forms of random factors in plant growth [26] (see Fig. 7). The L-system can use the leaf inclination as a control rule and a leaf area index as the constraint content. Therefore, this plant model can theoretically be coupled with microclimate simulation, and the calculation can be more accurate. At present, the L-system description method of plants has not been widely used in microclimate simulation, but the excellent effect of plant models on computer rendering can be regarded as at least an attempt in radiation calculation.

5. Plant modules

The task of a plant module is to link the plant description model with the basic meteorological parameters (temperature, wind speed, radiation, humidity). It can be then coupled to other modules of the calculation models (Fig. 1). The different effects on microclimate taken into account are summarized below.

5.1. Effects on radiation

Radiation models usually include sky model and environment model. Related to vegetation are environmental models. The radiant flux between objects in a space environment can be directly calculated by the Stefan-Boltzmann law, which does not require distinction between short-wave and long-wave radiation. However, this method is computationally expensive and difficult to apply. The way in which radiation fluxes are modified in and around urban structures can be described by the sky view factor (SVF), which is also an important parameter in urban climate studies [7]. Long-wave radiation in urban microclimate areas is mainly related to the visual factors of the sky [27]. The effect of vegetation on radiation is shown in Fig. 8. On the one hand, vegetation absorbs or reflects a large amount of shortwave radiation while transmitting a small amount of shortwave radiation, resulting in a "shadow" effect that significantly reduces solar heat absorbed by the shadow area; on the other hand, the vegetation and its surrounding environment continuously exchange heat by radiation.

According to Lindberg and Grimmond [9]; the mean radiant flux density (R, W m^{-2}) is defined as the sum of all fields of longwave (L_i, W m^{-2}) and shortwave (K_i, W m^{-2}) radiation fluxes in three dimensions

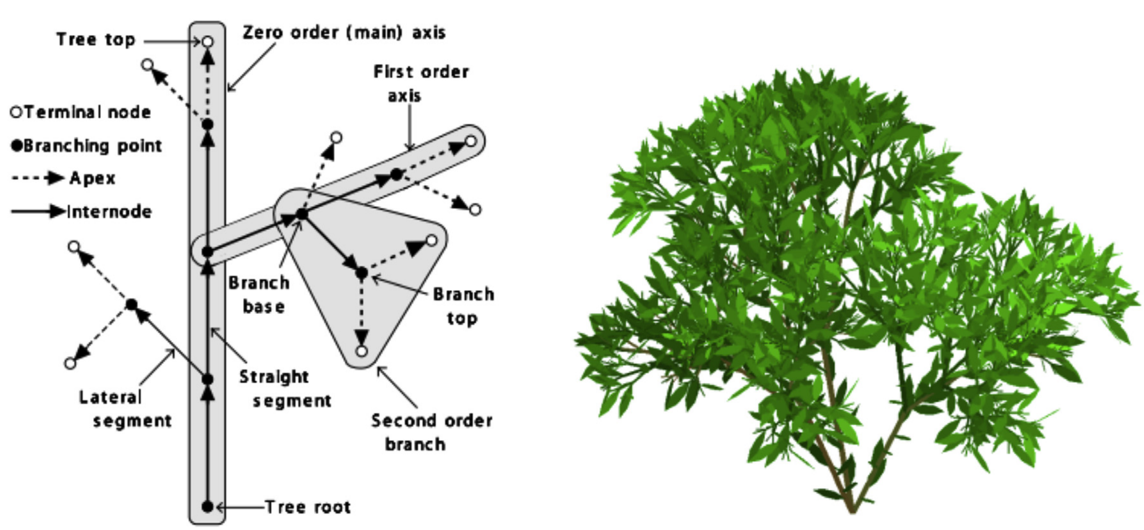

Fig. 7. Axial tree and final corresponding plant morphology based on L-system method (from Ref. [26] ©Springer, reprinted with permission of Springer Nature).

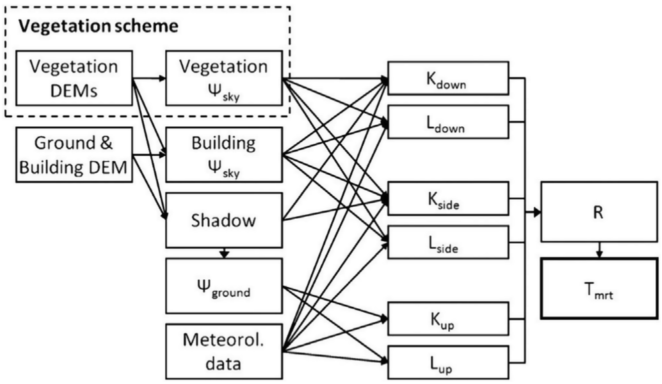

Fig. 8. Vegetation scheme in a radiation model (SOLWEIG) (from Lindberg and Grimmond, 2011©Springer, reprinted with permission of Springer Nature). DEM: digital elevation model; Ψ_{sky}: sky view factor; Ψ_{ground}: ground view factor; K, L: longwave and shortwave radiation fluxes (W m^{-2}), respectively, upward, downward and from the four cardinal points; R: mean radiant flux density (W m^{-2}); T_{mrt}: mean radiant temperature (°C).

(i = 1–6), together with the angular (F), absorption (ξ_k) and emissivity (ξ_p) factors of an individual:

$$R = \xi_k \sum_{i=1}^{6} K_i F_i + \varepsilon_p \sum_{i=1}^{6} L_i F_i \ (\mathrm{W\ m^{-2}}) \tag{1}$$

where F_i are the angular factors between a person and the surrounding surfaces. For a rotationally symmetric standing or walking person, F_i is set to 0.22 for radiation fluxes from the four cardinal points (east, west, north and south) and 0.06 for radiation fluxes from above and below. ξ_k is the absorption coefficient for shortwave radiation and ε_p is the emissivity of the human body with standard values of 0.7 and 0.97, respectively.

Under the ideal sky model and solar model, when the location and altitude angle of the sun are determined, the shadow range of a fixed vegetation at certain time is also determined. However, the radiation intensity in the shadow area is still greatly related to the extinction characteristics of the canopy: the light transmittance of the canopy differs due to the structural geometry, variety and leaf age. In addition, there is a big difference between extinction coefficients of vertical leaf groups and horizontal leaf groups. Not only that most vegetation is asymmetric, and some vegetation is heliotropism.

Therefore, although some models have established the radiation formula for LAD and transmission paths [28,29], the actual calculation still depends on the empirical parameters. For example, in the literature [30], the shortwave transmissivity of vegetation was taken to be 0.2 in Robitu et al. [31] and 0.3 in Lin [28]. Lindberg and Grimmond [9] provide a canopy transmissivity of deciduous tree throughout the year equal to 0.43, 0.20, 0.07, 0.02, and 0.05 for the evergreen trees. Similarly, the reflectivity and emissivity of vegetation are also on empirical values.

Some 3D models, such as ENVI-met, use the flux reduction coefficient to evaluate the effects of plants on radiation, and the coefficient is exponential with the LAI, which is negatively correlated with the sky visibility coefficient [32]. Another great advantage of this method is that the biological physical model of plants is associated with the radiation model.

5.2. Aerodynamic effects

The main impact of vegetation on the environment is the reduction of air velocity due to drag force, and the additional turbulence levels produced by the canopy elements. These effects are represented by a porous-media approach based on superficial velocities where momentum sinks (Su_i) and turbulence sources are applied to a block of cells chosen to represent the tree canopy. The drag resistance is related to the drag coefficient of the vegetation C_d, LAD, the air density ρ (kg m^{-3}), the wind speed U (m s^{-1}) and the wind velocity component u_i (m s^{-1})

$$Su_i = -\rho LADc_d U u_i \quad (\mathrm{Pa\ m^{-1}}) \tag{2}$$

The turbulent interaction between the airflow and the plant canopy is simulated by including the following additional source terms in the transport equations for k and ε:

$$S_k = \rho LADc_d(\beta_p U^3 - \beta_d Uk) \ (\mathrm{kg\ m^{-1}\ s^{-3}}) \tag{3}$$

$$S_\varepsilon = \rho LADc_d\left(C_{\varepsilon4}\beta_p \frac{\varepsilon}{k} U^3 - C_{\varepsilon5}\beta_d U\varepsilon\right) \ (\mathrm{kg\ m^{-1}\ s^{-4}}) \tag{4}$$

where β_p, β_d, $C_{\varepsilon4}$ and $C_{\varepsilon5}$ are empirical constants. An extensive description and summary have been recently given by Buccolieri et al. [33] in their review on urban tree modelling in CFD simulations.

5.3. Heat and humidity model

The heat and humidity model of vegetation is used to describe the heat and moisture transfer inside and outside of the vegetation, such as heat and moisture transfer caused by transpiration. The empirical derivation of the surface temperature of plant canopy is given in the literature [34]. Some models [10] put forward the energy balance equation of the vegetation:

$$\Delta Q(t) = \Delta Q_E(t) + \Delta Q_P(t) + \Delta Q_H(t) \quad (\mathrm{W\ m^{-2}}) \tag{5}$$

where ΔQ indicates the net energy absorbed by the tree canopy. ΔQ_E is the energy of vegetation evaporation; ΔQ_P is the energy stored by the vegetation; ΔQ_H is the heat transfer between vegetation (mainly the canopy) and the surrounding air. However, the amount of vegetation heat storage ΔQ_P and the evaporation heat dissipation ΔQ_E are difficult to evaluate. A linear relationship related to vegetation heat dissipation, solar radiation level and ambient air temperature was derived by Jensen et al. [35]. However, since the evaporation and heat dissipation of vegetation strictly depend on the stomatal system of vegetation, this conclusion is limited by the geographical environment and vegetation species. Another study pointed out that the evaporation volume of ΔQ_E and the convective heat transfer Q_H meet the Bowen rate β without considering the heat storage capacity of vegetation [30], but the condition of the relation is that the radiation or the wind field does not change with time. The ENVI-met model is one of the most comprehensive models which include the vegetation water balance model. By establishing the relationship between the parameters of plant root area coefficient, LAI and environmental physical quantity, ENVI-met can reflect the effects of transpiration, stomatal opening and soil water content on the heat and humidity environment.

6. Brief description of the selected microclimate models

The microclimate models which take into account the effects of vegetation are almost all existing models where those effects are implemented through a plant module and coupled with other modules. A brief description of the EBM and CFD models, as well as an example of coupling, is reported below. The reader is referred to Section 3 for references of each model.

6.1. The Energy Balance Models

RayMan can be used to estimate radiation flux, clouds, solid obstructions for shortwave radiation. The trees in the software are regarded as obstacles and it can only modify the position, shape and size of trees, and the attributes of trees cannot be set independently. Since the model does not consider the multiple reflection between objects, the mean radiant temperature T_{mrt} value of the model is significantly lower when the solar altitude angle is low [36], which may lead to the overestimation of the cooling effect of trees. Therefore, the application of RayMan in high latitudes is limited. The 3D radiation model SOLWEIG has partially solved the deficiencies of RayMan by improving the calculation method of radiation space. The setting of trees in SOLWEIG is friendly, and the parameters such as transmittance and reflectivity can be set according to different situation. Because diffusion and reflection formula of solar radiation is based on a simplified method, it is not suitable for high density urban space (SVF < 0.65) [8]. Both RayMan and SOLWEIG can be combined with digital elevation models (DEMs) and can manage the complex terrain environment.

The CTTC model uses the method of building thermal time constant to calculate the 3D lumped parameter model of the air temperature in the local building environment changing with the external heat disturbance [37,38]. After the introduction of the vegetation module, it is named green-CTTC model. The temperature of the urban building group obtained by the CTTC model is related to the different solar radiation and long wave radiation. As the canopy temperature is close to the observed ground temperature, the variation of long wave radiation caused by vegetation is very small. Therefore, the main correction of the green CTTC model is the solar radiation model. The model can be used to deduce the relationship between the parameters such as average greening coverage and climate regulation. Researchers at South China University of Technology have implemented the green CTTC model on the CAD platform DUTE (Design Urban Thermal Environment). DUTE can define shading, transmittance and crown characteristics of trees, and support the custom parameters of all kinds of underlying surfaces. It can get the average solar radiation absorption coefficient of the underlying surface to compare the different designs. The software has a friendly interface and it is suitable for designers. However, since CTTC model needs more verification in accuracy [39], DUTE tool has not been widely used.

The TEB-veg is based on new radiation calculations for a canyon composed of a portion of road and garden. Orientation of the road and distinction of the thermal evolution of the two walls are also available. It takes into account the shadow effects for gardens. The surface exchanges between vegetation and atmosphere are then calculated by considering the “real” short- and long-wave radiation received by gardens, as well as microclimatic conditions (temperature, humidity and wind) within the canyon instead of those above the top of the canopy. Inversely, the microclimate within the canyon is resolved by including the contributions from gardens in heat, moisture and momentum.

Some of the EBM models have also been reviewed by Grimmond et al. [40].

6.2. CFD models

CFD software such as OpenFOAM, FLUENT and STAR-CCM + may account for the aerodynamic and thermal effects on the airflow in the Reynolds-Averaged Navier-Stokes (RANS) equations. The commercial CFD software PHOENICS has developed the plant canopy module FOLIAGE.

As emerges from the review of literature studies (Section 3 and Appendix A), FLUENT and OpenFOAM are mainly used to study the impact of vegetation on ventilation and air quality (see for example [41–43]. Recently, Toparlar et al. [44] conducted a review on the CFD analysis which confirms what found here that ENVI-Met is the most used software for urban microclimate analysis (see Fig. 1). In particular, a recent study [45] has shown that this model is a viable tool to assess the effects of trees on the urban microclimate, especially transpiration cooling effects. It takes into account the vegetation influence on atmosphere, radiation, soil and turbulence. In addition, the software brings a sizable vegetation database and supports the editing of custom vegetation. ENVI-met can be combined with DEMs and can manage the complex terrain environment. Therefore, the software is subject to the long-term concern of microclimate researchers (see the recent review by Ref. [46].

6.3. Coupling techniques

As it emerges from the review of literature studies, both EBM and CFD models have been coupled with other software to investigate a phenomenon in great detail, analyse different effects, complex urban environment, maximize the advantages and compensate the limitations,. In particular, most of the studies have coupled ENVI-met with RayMan to improve its capability and overcome its limitations (e.g. no consideration of heat storage in buildings [47]), inaccurate measure of T_{mrt} [48], the limited options for grid generation etc.). Below as an example of coupling and application, the recent study by Huang et al. [49] is reported. The reader is referred to Appendix A for all the other studies collected in this review.

Huang et al. [49] assessed hazard, exposure and vulnerability aspects to identify thermal risk in a traditional settlement in hot-and-humid Tainan, Taiwan. Hourly future climate data were constructed based on morphing method with a general circulation model (GCM) and thermal stress map was produced by ENVI-met and future thermal comfort was simulated by RayMan. ENVI-met, in combination with RayMan, were thus respectively used for identifying current spatial distribution of thermal stress and for assessing the future thermal comfort changes and the effectiveness of proposed shading adaptation measures to counteract climate change.

It is worth mentioning the recent study by Nice et al. [50] who have developed a new micro-scale model, VTUF-3D v1.0 (Vegetated Temperatures of Urban Facets), to examine the influence of urban vegetation on human thermal comfort (HTC) [51]. This model uses the MAESPA process-based tree model [52] and TUF-3D [53] urban microclimate surface energy balance (SEB) model. From the comparison with previous studies, VTUF-3D, with the addition of vegetation and Q_E fluxes, has shown significant improvement over TUF-3D model. Moreover, it is able to perform with high level of accuracy at a microscale.

7. Evaluation indices

For the purpose of this paper, the evaluation of urban outdoor microclimate includes the evaluation of wind and thermal environment.

As for the wind environment, the evaluation indices include wind pressure, wind speed, wind speed magnification coefficient and so on. Some specific ventilation indices, such as the mean age of air, the visitation frequency, the net escape velocity and others have been proposed in the literature to evaluate the ventilation ([54], but they are not discussed here since they are strictly related to flow, turbulence and pollutant concentration (PC). As for air quality, different air quality indices (AQI) based on pollutant concentrations are used by government agencies to communicate to the public how polluted the air currently is or is forecast to become.

As for thermal environment and comfort, the indices can be divided into three types summarized in Table 2, which shows only the indices employed in the 97 studies.

Specifically:

1. meteorological indices are based on the direct use of one or several elements of physical index evaluation, such as the wet bulb temperature, globe temperature, humidity, solar radiation etc. Such indices do not consider the body's reaction;
2. thermal indices take into account the physiological reaction and physical environmental factors. Researches based on regression analysis and experimental data have been performed to derive some hot environmental risk early warning indices, such as wet-bulb-globe temperature (WBGT) [55], heat island index [56], urban heat island index (UHII), humidity index (Humidex) [57], apparent temperature (AT) [58], mean radiant temperature (T_{mrt}) [59]. However, these indices are difficult to apply to different

Table 2
Microclimate evaluation indices (output parameters) employed in the reviewed 97 studies. Please note that some CFD models were coupled with EBM models for thermal evaluations (see Appendix A for further details).

Microclimate model		Meteorological indices	Thermal indices	Thermal comfort indices
EBM	RayMan	–	–	PET
	SOLWEIG	–	T_{mrt}	–
	CTTC	T_{air}	–	–
	TEB-veg	T_{air}, RH		
CFD (used alone or coupled with EBM models)	PHOENICS	T_{air}, T_{surf}	–	CP
	FLUENT	T_{air}, T_{surf}, RH	T_{mrt}	PMV
	OpenFoam	–	–	–
	STAR-CCM+			
	ENVI-met	T_{air}, T_{surf}, RH	T_{mrt}, WBGT, UHII	PMV, PET, TEP, OUT-SET

Note: T_{air}: air temperature (°C); T_{surf}: surface temperature (°C); RH: relative humidity (%); T_{mrt}: mean radiant temperature (°C); WBGT: wet-black-globe temperature (°C); UHII: urban heat island index (°C); PET: physiological equivalent temperature (°C); CP: cooling power (mcal $cm^{-2} s^{-1}$); PMV: predicted mean vote (dimensionless); TEP: temperature of equivalent perception (°C); OUT-SET: outdoor standard effective temperature (°C).

geographical regions and climate types;

3. thermal comfort indices are further combined with the human subjective feelings of the environment, in the steady state assumption on the basis of experience obtained, such as effective temperature (ET) [60], standard effective temperature (SET) [61], outdoor standard effective temperature (OUT-SET) [62], perceived temperature (PT), predicted mean vote (PMV) corrected with the expectation factor (PMVe) [63], Munich energy balance model for individuals (MEMI) [64], physiological equivalent temperature (PET) [65,66], universal thermal climate index (UTCI) [67], Man - ENvironment heat EXchange (MENEX), comfort formula (COMFA) [68] and its modified equation [69], temperature of equivalent perception (TEP) [70], cooling power (CP) [71] etc. Some of the thermal comfort indices have been reviewed by, for example, Monteiro [72]; Epstein and Moran [73]; Honjo [74]; Walls et al. [75]. It should be noted that steady models are now widely used in the indoor environment evaluation, based on the assumption that the human body and the environment of heat exchange are in a steady-state, while the outdoor environment is changing the human body heat load, and the thermal dynamic environment feeling, so indices based on the steady-state comfort model still have some defects.

In Fig. 9 the number of studies employing different evaluation indices is reported. The meteorological indices have been the most investigated (70 studies), in particular T_{air} has been analysed in 58 studies and wind speed WS in 26 studies. 18 studies investigated the role of vegetation on pollutants concentration PC. Please note that the total number of studies in the figure is larger than 97 since there are studies employing several indices (see Appendix A).

Even though the meteorological indices are the most employed, the thermal comfort indices allow evaluating the whole impact of vegetation on microclimate and in particular on thermal comfort, since they consider the subjective and objective feelings of the human body and the complexity of the model computation as well as the physical factors of the environment. Also, some of the thermal indices, such as the T_{mrt}, are also taken into account in the calculation of thermal comfort indices such as PMV and PET.

It is important to note that the calculation of some of the indices in different models may be different. For example, PHOENICS and CTCC-DUTE use two different simplified formulas for WBGT; the PMV calculation model for outdoor assessment in ENVI-met is based on a revised version of the indoor evaluation [76]. Therefore, it is necessary to pay attention when comparing the same index obtained by different software.

8. On the choice of the modelling approach

Outdoor human comfort is affected by urban planning and design and affects the liveability of a city, thus strategies for its improvement are needed. These include shading structures, water bodies, green areas and in general the enhancement of natural ventilation. Vegetation in particular has a major impact as it provides shading and improves the whole urban microclimate. But a correct planning of vegetation is needed to optimize its benefits and avoid undesirable effects.

In the literature, thermal comfort has been evaluated by means of measurements and numerical modelling. Thermal comfort indices incorporating several microclimate factors have been introduced as summarized in the present review.

The increasing availability of computational resources has leaded to the development and application of numerical simulation approaches which, compared with field or wind tunnel experiments, allow to evaluate different scenarios, make comparative analyses and provide information on all the investigated variables in the whole computational domain. Among the modelling tools, a distinction is made between EBM and CFD. EBM models are based on the law of energy conservation for a control volume and allow investigating many factors of thermal environment. Although these models cannot provide the specific distribution of temperature or humidity field, they can quickly calculate the physical quantity of the whole environment, which is suitable for a preliminary screening in a design evaluation plan. Simulations with CFD are frequently used to assess urban microclimate. CFD can resolve the transfer of heat and mass and their interaction with individual obstacles such as buildings. Compared to EBM, CFD is capable of performing simulations with the explicit coupling of velocity, temperature, humidity and pollution fields, and resolves the flow field at finer scales (e.g. building or even human scale) than EBM. However, CFD simulations require a high-resolution representation of the urban geometry, the knowledge of boundary conditions for all relevant flow variables and adequate computational resources [44].

Based on the present review some useful features and suggestions, mostly vegetation-related, have been collected for each model to help the model users to select the proper model, which takes into account the effects of vegetation on urban outdoor microclimate, depending on the specific objective.

8.1. Input, output and vegetation-related characteristics

The main factors influencing the urban microclimate are generally the surface geometry, the thermal properties of the materials, the surface imperviousness, the anthropogenic heat. The thermal conditions which affect the comfort are mostly related with temperature, wind, humidity. All these factors can be included (as input parameters) into a model which integrates the surface geometry (buildings, vegetation and any other urban obstacles) and the thermal properties of urban materials, the anthropogenic heat, the surface imperviousness. Table 3 summarizes the main input parameters of the EBM and CFD models selected in this review, as well as the meteorological, thermal and thermal comfort indices which constitute the output of the simulation process. In the table a particular attention is given to the vegetation species and types which are directly implemented and available in each model. Further Table 4 reports on the main vegetation-related processes already implemented in each model.

8.2. Strengths, weaknesses and measures for model output improvement

Finally, in order to provide the reader with further indications and suggestions on the choice of the proper model which takes into account

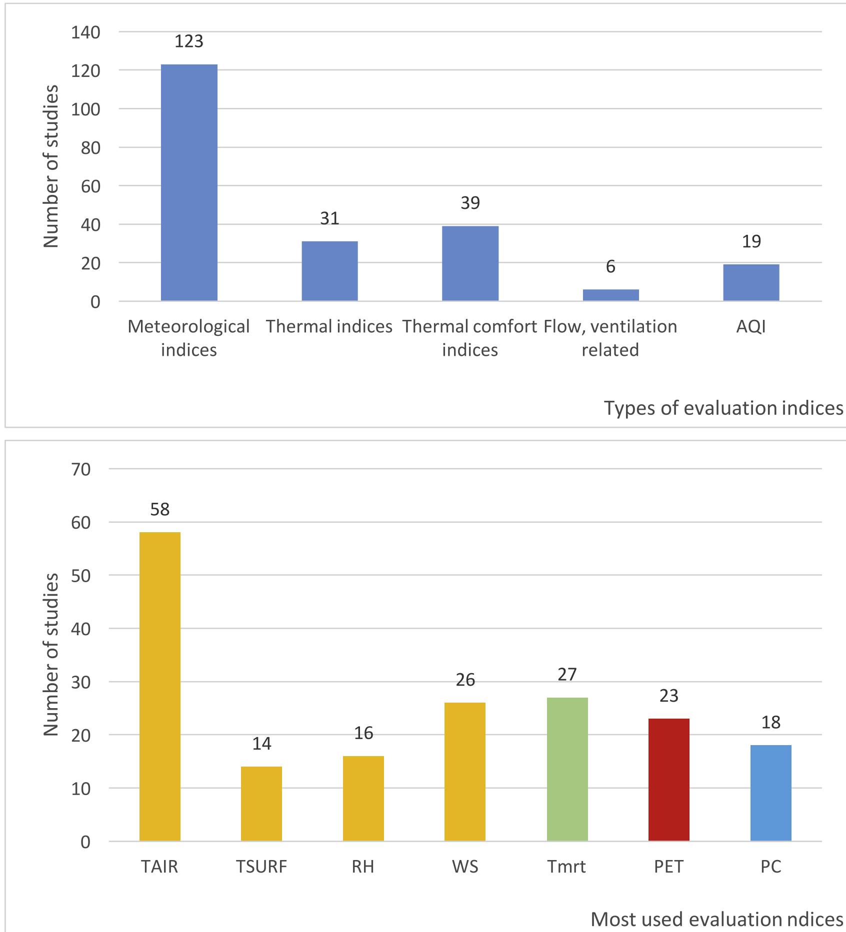

Fig. 9. Distribution of the 97 studies based on the types of evaluation indices (top) and the most used evaluation indices (bottom), where the bars are colored based on the types of indices: yellow = meteorological indices; green = thermal indices; red = thermal comfort indices; blue = AQI. The total number of studies is larger than 97 since there are studies employing several indices (see Appendix A). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the effect of vegetation on urban microclimate, Table 5 collects main general strengths and weaknesses of each model, mostly related to thermal comfort evaluation, and suggestions for model output improvement.

9. Conclusions

Studies using EBM and CFD models evaluating the impact of vegetation on urban outdoor microclimate were reviewed. The whole process was focused on summarizing current features related to the inclusion of vegetation in urban microclimate models, such as the plant representation, the plant effects, the types of microclimate models which implement such effects and the evaluation indices employed to assess the effects of vegetation on outdoor microclimate (i.e. temperature, humidity, wind flow and thermal comfort). This review strictly identifies microscale studies investigating urban outdoor microclimate (including thermal comfort) in the presence of vegetation, using one or more evaluation indices. The review is not exhaustive but may help the user to select the proper model to take into account the effects of vegetation on outdoor urban microclimate.

The starting point was the "plant evaluation model", a common framework for simulation where vegetation-related components ("plant description" and "plant module") have been implemented. Main features and findings arisen from this review are summarized below:

- there exist five degrees of simplification of "plant description" in the literature: ideal canopy model, statistical method, geometry method, measurement and representation method, L-system method. Different models adopt different plant description. For example, ENVI-met adopts the geometry method which discretizes the space by mesh generation, thus preserving the approximate form of plants where the LAI may change with spatial location;
- the "plant module" links the plant description model with the basic meteorological parameters. The different effects taken into account are the effects on radiation, the aerodynamic effects and the heat and humidity model. While EBM models commonly include effects on radiation and the heat and humidity model, CFD models have been mostly employed to evaluate the aerodynamic effects, but ENVI-met which implements all the effects;
- evaluation indices employed for the assessment of the impact of vegetation on microclimate are divided into three types. While the first type (meteorological indices) is that most employed in the reviewed studies, the third type (thermal comfort indices) allows to evaluate the whole impact of vegetation on microclimate and in particular on thermal comfort, since it considers the subjective and objective feelings of the human body and the complexity of the model computation as well as the physical factors of the environment; - among the CFD models, ENVI-Met has been the most used software for urban microclimate analysis as it already implements the main vegetation processes to take into account effects of vegetation on atmosphere, radiation, soil and turbulence.

Table 3
Main input, output and vegetation types available in the reviewed microclimate models.

Microclimate model		Input	a. Vegetation species b. Type of vegetation c. 3D greening model	Output
EBM	RayMan	- Urban morphological data - T_{air} - Vapour pressure - WS	a. No b. Deciduous/coniferous trees c. No	- T_{MRT} - PET - PMV - UTCI - SET - PT
	SOLWEIG	- Digital Surface Model - Direct, diffuse and global shortwave radiation - T_{air} - RH	a. No b. Deciduous/coniferous trees/bushes c. No	- T_{mrt}
	CTTC	- Urban geometric data (H/W, building density etc) - Direct, diffuse radiation - Solar azimuth, altitude - T_{air} - Vapour pressure - Cloud cover - WS Anthropogenic heat	a. A couple of empirical species for reference b. Deciduous/coniferous trees/bushes c. No	- T_{air}
	TEB-veg	- Urban geometric data (height/width, roughness length etc.) - Radiative parameters (albedo, emissivity) - WS, T_{air}, RH	a. No b. Deciduous/coniferous trees/bushes c. No	- WS - RH - T_{air} - T_{soil}
CFD	PHOENICS	- Urban geometry with mesh - Boundary conditions - Meteorological variables	a. A couple of empirical species for reference b. Various c. Yes	- Meteo indices
	FLUENT OpenFoam STAR-CCM+		a. No b. Various c. Yes	
	ENVI-met	- Area input file (buildings, vegetation, type of soil, receptor, domain information) - Meteorological parameters (T_{air}, RH, WD, WS, roughness length) - Project features (pollutants, timesteps, soil, solar adjustment etc.)	a. Abundant, with roof greening and vertical greening b. Various c. Yes	- Meteo indices - T_{MRT} - PMV/PPT - PET - UTCI - SET

The development of software technology brings more opportunities to the application of the plant evaluation model. Large data, cloud computing and parallel computing will make the future numerical simulations (especially CFD) faster and more stable, and the practicability will be greatly enhanced. It is also expected an increase of the coupling between microclimate models and both mesoscale models. Finally, as already implemented in the last version of ENVI-met, the use of DEMs through CAD and/or GIS may help to improve the representation and spatial location of the real building environment. In this regard, the recent EBM model UMEP [77], written as a plug-in QGIS, has been proposed as an integrated tool for urban climatology and climate sensitive planning applications. It can be used for a variety of applications related to outdoor thermal comfort, urban energy consumption, climate change mitigation etc. as it implements other models.

Finally, it is worth noting that this review is based on studies analysing the effects of vegetation on thermal environment from the perspective of human being. However, growing and living conditions of trees in the urban environment may be hostile due to limited rooting space, light or extreme local conditions which can hinder a successful development of the plant. Tools specialized in assessing the effects of microclimate on plants may be important for agricultural and landscape researchers. As an example, the new ENVI-met module TreePass has been announced in the official website and will provide a comprehensive data sheet of all relevant growing conditions and look at the trees biomechanics to prevent storm damage. The TreePass will be able to analyse individual trees considering the crown geometry with the resolution of a single branch using the L-System method approach for

Table 4
Vegetation-related processes and characteristics available in the reviewed microclimate models.

Microclimate model		Form and material of ground and façade	Seasonal variation of vegetation	Radiation transmittance of vegetation	Radiation emission of vegetation	Transpiration	Photosynthesis	Turbulent effect of vegetation	Effect of plant module on computational speed
EBM	RayMan	×		√		×			Small
	SOLWEIG								
	CTTC	√					×		Moderate
	TEB-veg	×		√				×	
CFD	PHOENICS	√	×					√	Moderate to large
	FLUENT								
	OpenFoam								
	STAR-CCM+								
	ENVI-met	√							

Note: √ denotes Yes, × denotes No.

Table 5
Strengths, weaknesses, mostly related to thermal comfort evaluation, and suggested measures for output improvement.

Microclimate model		Strengths	Weaknesses	Measures for improvement Integration
EBM	*RayMan*	- Shadowing by obstacles like building and trees - Computationally fast - User-friendly interface - Support for importing simple inx. file generated by early ENVI-met or other DEM file for model.	- Accuracy of thermal comfort calculation depends on user's input value of wind speed - Applicability in high latitudes - Long-wave radiation from plants and other elements is not strictly distinguished - The radiation model is inaccurate in the evening due to the lack of material property settings, such as thermal inertia	- Improvement of the quality of wind speed input data which affect the thermal comfort evaluation
	SOLWEIG	- The radiation model is modified - Computationally fast - User-friendly interface - Combination with DEM terrain file	- Few meteo parameters are needed as input data - No nocturnal T_{MRT} analysis - No thermo-physiological indices (such as PET) - Same as Rayman last point	- Combination with other tools to calculate Thermal Comfort Index
	CTTC	- Computationally fast, with convection considered - Applicability to a wider range of weather conditions and urban landscapes - Detailed analysis of radiant exchange - Simplified methods to describe the effect of vegetation and anthropogenic heat sources	- The convective heat transfer model uses a large number of empirical coefficients - When the influence of convection is great, thermal comfort values are quite different from the actual values - No spatial distribution of outputs	- Establishment of the magnitude of the effect on canyon air temperature of such mesoscale features, considering their distance from the street in question, wind direction and the intensity of the fluxes
	TEB-veg	- Accurate and complex radiation exchange calculation	- The vegetation is considered as an open area that is not subject to shadow effects of buildings and to radiation trapping within the canyon - Unrealistic geometric parameters - the 2-m air temperature and humidity are simply calculated as an arithmetic average of the 2 m air temperature and humidity provided independently by the two models - Not suitable for open areas	- Combination with a CAD model for a better representation of urban geometry
CFD	PHOENICS	Good infrastructure for developing modular applications	- No coupling between modules - Some issues with thermal environment evaluation	- Powerful computer or cloud computing to speed up simulation - More suitable model coefficient incorporated with experimental measurement
	FLUENT	- Many editable options - Many turbulence models	- Settings are complex - Computationally expensive in complex conditions	- Powerful computer or cloud computing to speed up simulation
	OpenFoam	- Many editable options - Many turbulence models - Open source	- Settings are complex - The accuracy of calculation depends on the user's ability to edit scripts - Computationally expensive in complex conditions	
	STAR-CCM+	- Many editable options - Many turbulence models	- Settings are complex - Computationally expensive in complex conditions	
	ENVI-met	- Small-scale interactions between buildings, surfaces and plants; - User-friendly interface - Possibility to create several types of vegetation - Plant models are fully considered and very practical - Support import CAD\GIS file even OpenStreet Map - Output results are binary standard files, third-party readability is strong	- The turbulence model tends to overestimate the turbulent production in high acceleration areas - Computationally expensive in complex conditions	

plant description. The effect of local growing conditions, such as access to light, will be taken into account as well as different maintenance strategies. This perspective will strengthen the study of the relationship between vegetation and microclimate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.05.029.

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