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# Review on urban tree modelling in CFD simulations: Aerodynamic, deposition and thermal effects

Riccardo Buccolieri[a,*], Jose-Luis Santiago[b], Esther Rivas[b], Beatriz Sanchez[b]

[a] Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, S.P. 6 Lecce-Monteroni, 73100 Lecce, Italy
[b] Environment Department, Research Center for Energy, Environment and Technology (CIEMAT), Spain

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ABSTRACT

This paper reviews current parameterizations developed and implemented within Computational Fluid Dynamics models for the study of the effects linking vegetation, mainly trees, to urban air quality and thermal conditions. In the literature, passive mitigation via deposition is parametrized as a volumetric sink term in the transport equation of pollutants, while a volumetric source term is used for particle resuspension. The aerodynamics effects are modelled via source and sink terms of momentum, turbulent kinetic energy and turbulent dissipation rate. A volumetric cooling power is finally considered to account for the thermal (transpirational cooling) effects of vegetation. The most recent applications are also summarized with a focus on the relative importance of both aerodynamic and deposition effects, together with recent studies evaluating thermal effects. Those studies have shown that the aerodynamic effects of trees are stronger than the positive effects of deposition, however locally the pollutant concentration increases or decreases depending on the complex interrelation between local factors such as vegetation type and density, meteorological conditions, street geometry, pollutant characteristics and emission rates. Unlike aerodynamic and deposition effects on pollutant dispersion which were also found in street far from trees, the thermal effects were in general locally restricted to the close vicinity of the vegetation and to the street canyon itself. Future requirements in CFD modelling include more in depth investigation of resuspension and thermal effects, as well as of the VOCs emissions and chemical reactions. The overall objective of this review is to provide the scientific community with a comprehensive summary on the current parameterizations of urban vegetation in CFD modelling and constitutes the starting point for the development of new parametrizations in CFD as well as in mesoscale models.

## 1. Background

The urban population in 2015 accounted for 54% (4 billion) of the total global population and it is expected to increase to 60% (4.9 billion people) of world population by 2030 (UN-Habitat, 2016). People often breathe air that does not meet the legislation standards making urban air quality one of the most important environmental challenges and the largest environmental health risk in Europe (EEA, 2015). Together with legislative actions to improve air quality, several scientific works have been conducted on the potential of urban vegetation as mitigation tool for air quality improvement, carbon sequestration, micro-climate regulation, noise reduction, rainwater drainage, airborne pollution modification (Salmond et al., 2016; Livesley et al., 2016). Psycho-logical and recreational values were also reported by Haaland and van den Bosch (2015), who reviewed benefits and challenges associated with implementing the compact city approach by looking at the effects of urban densification and compact city development on urban green space and its planning. Their review underlines that provision of urban green space in compact city environments and during densification processes is still a major challenge. Loss of private urban green space rarely is counterbalanced by provision of more public green space. Several ways are identified to deal with these challenges, e.g. how loss of green space quantity can be offset by increased green space quality. A systematic review of epidemiological studies on health benefits of green spaces in the living environment has been recently provided by Van den Berg et al. (2015), who showed a strong evidence for significant positive associations between the quantity of green space and perceived mental health and all-cause mortality, and a moderate evidence for an association with perceived general health.

When dealing with air quality at local scale, urban vegetation, especially trees, as well as other obstacles and barriers, have been demonstrated to influence flow patterns and thus the levels of pollutant concentrations (see recent reviews by Gallagher et al., 2015; Janhäll, 2015; Grote et al., 2016; Abhijith et al., 2017). Some green

* Corresponding author.
*E-mail address:* riccardo.buccolieri@unisalento.it (R. Buccolieri).

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infrastructures as vegetation barriers (e.g. hedges) can potentially improve urban air quality acting as a barrier between traffic emissions and population. In addition, pollutant concentration is mitigated by means of deposition on these green infrastructures. However, the impact of street trees is more complex and reduce or increase the concentration depending on the case. Results have highlighted the complexity and the need for a careful design of vegetation structures to optimize benefits and reduce the potential for unintended consequences. A systematic evaluation of the impact of vegetation health, height, species, density, distance from the road, or leaf area index (ratio of leaf area to ground area, LAI) on the processes determining pollutant dispersion, deposition and atmospheric chemistry has been recently provided by Abhijith et al. (2017), who attempted to review the inter-relations between local factors such as vegetation type and density, climatic conditions, street geometry, pollutant characteristics and emission rates. There remains however considerable controversy as to whether increased vegetation within urban areas has the potential to provide a positive or negative contribution to local scale air quality.

In reviewing past works on such topics, it is worth noting that aerodynamic and deposition effects have been separately investigated in simple geometries, and only few recent studies have brought them together to enable an appreciation of their relative influence and how they interact in real scenarios. Further, very limited studies have recently accounted for resuspension and thermal effects of vegetation on street temperatures, which, in turn, affect flow pattern and pollutant distribution.

In this context, this paper focuses on the parametrizations of the effects of urban vegetation, trees in particular, on flow and pollutant dispersion in urban areas by reviewing the most recent Computational Fluid Dynamics (CFD) microscale simulations. The overall objective is to provide the scientific community with a comprehensive overview on the current parameterizations of aerodynamic, deposition, resuspension and thermal effects of trees in CFD models (Fig. 1), as well as insights on the relative importance of aerodynamic and deposition effects on flow and pollutant concentration. This review could constitute a systematic summary for scientists interested in modelling vegetation in their studies and the starting point for the development of new parametrizations in CFD models as well as in mesoscale models, which is an open question for the scientific community.

## 2. Brief overview of regulating (dis)services of urban street trees

The recent papers by Salmond et al. (2016) and Livesley et al. (2016) have systematically reviewed works analysing the role of street vegetation, mainly, trees in provision of regulating (dis)services which are briefly summarized here:

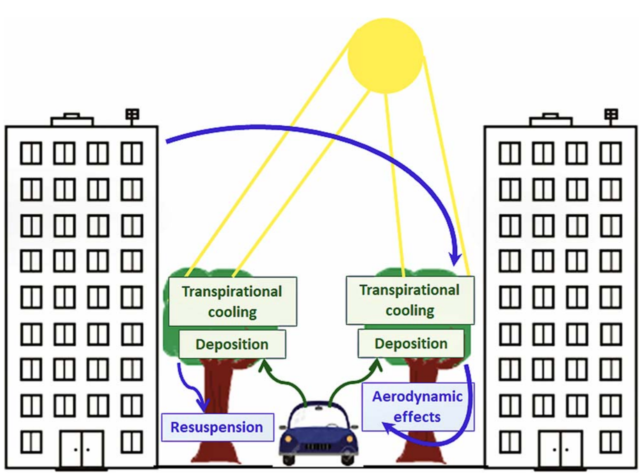


**Fig. 1.** Effects of street trees parametrized in CFD models and discussed in the present review.

- *microclimate regulation*: increasing vegetation in urban areas may lead to reduced ambient and surface temperatures and increased evapotranspiration, precipitation interception and reduced runoff. This is an effective option for mitigating urban heat and adapting to climate changes caused by regional-scale changes in land use and global scale changes in atmospheric composition (Gill et al., 2007). Local reductions in temperature may change the rate of chemical reactions within the atmosphere, leading to reduced concentrations of other pollutants such as ozone;
- *noise attenuation*: little is known about the specific value of street trees in reducing noise pollution in street canyons, although there is certain evidence that trees can attenuate traffic noise roadside of open busy streets (Kalansuriya et al., 2009);
- *emission of biogenic volatile compounds*: street trees directly emit gases precursors to the formation of secondary pollutants such as ozone. Trees emit biogenic volatile organic compounds (bVOCs) as a reaction to stress in their environment, such as high light intensities and/or temperatures or low water availability (Seinfeld and Pandis, 2006; Leung et al., 2011). In the presence of $NO_x$ and sunlight, VOC contribute to ozone and particulate formation, which may accumulate locally when ventilation is limited (Calfapietra et al., 2013);
- *pollen release*: exposure to allergenic pollen produced in the flowers of trees is associated with a range of health effects. The timing of the release varies depending on the tree species and environmental conditions (Cariñanos et al., 2016). Dispersion of tree pollen is dependent on a number of environmental factors, including local meteorological conditions;
- *absorption and deposition of pollutants*: street trees have the potential to regulate air quality by absorbing pollutants and increasing pollutant deposition. Trees increase both the surface roughness (slowing air flow thus enhancing deposition and absorption pollutant removal processes) and the area of the ground surface that atmospheric pollutants come into contact with (acting as biological filters, enhanced by the properties of their surfaces). Trees absorb $CO_2$ and gaseous pollutants such as $O_3$, $NO_2$, $SO_2$ primarily by uptake via leaf stomata or surface, and accumulate airborne particulates (by interception, impaction or sedimentation) more effectively than other urban surfaces (Escobedo and Nowak, 2008; Janhäll, 2015).

As for air quality at local scale, as already mentioned in the Introduction, the atmosphere-urban vegetation interaction is complex and it is needed a careful design of green infrastructure to optimize air quality improvements and reduce unintended consequences.

## 3. Brief overview of experimental studies for CFD validation purposes

Both field and wind tunnel investigations have looked at the effects of urban vegetation, mainly trees, hedges and other vegetation barriers, on flow and pollutant concentrations in urban areas. While most field experiments were performed in real scenarios, wind tunnel experiments mainly considered idealized cases of isolated trees or located within simple street canyons. For a comprehensive review see Abhijith et al. (2017). Here a brief overview of wind tunnel studies which are used for CFD validation purposes is provided.

In full-scale field tests flow and concentrations are measured under real atmospheric conditions. They have the advantage that the full complexity of a real problem is considered even though they are limited by low spatial resolution and uncontrollable meteorological conditions. As for vegetation, the main advantage is that the "real" effect has been considered, but it is not likely to distinguish between aerodynamic, deposition, resuspension and thermal effects on concentration levels. This makes field tests not suitable for evaluating the relative contribution of those effects, even though they are important to validate modelling simulations under real conditions.