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Leaf trapping and retention of particles by holm oak and other common tree species in Mediterranean urban environments

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ABSTRACT

Holm oak (*Quercus ilex*), a widespread urban street tree in the Mediterranean region, is widely used as biomonitor of persistent atmospheric pollutants, especially particulate-bound metals. By using lab- and field-based experimental approaches, we compared the leaf-level capacity for particles' capture and retention between *Q. ilex* and other common Mediterranean urban trees: *Quercus cerris*, *Platanus* × *hispanica*, *Tilia cordata* and *Olea europaea*. All applied methods were effective in quantifying particulate capture and retention, although not univocal in ranking species performances. Distinctive morphological features of leaves led to differences in species' ability to trap and retain particles of different size classes and to accumulate metals after exposure to traffic in an urban street. Overall, *P.* × *hispanica* and *T. cordata* showed the largest capture potential per unit leaf area for most model particles (Na^+ and powder particles), and street-level Cu and Pb, while *Q. ilex* acted intermediately. After wash-off experiments, *P.* × *hispanica* leaves had the greatest retention capacity among the tested species and *O. europaea* the lowest. We concluded that the *Platanus* planting could be considered in Mediterranean urban environments due to its efficiency in accumulating and retaining airborne particulates; however, with atmospheric pollution being typically higher in winter, the evergreen *Q. ilex* represents a better year-round choice to mitigate the impact of airborne particulate pollutants.

Introduction

Urban population is increasing worldwide and a further rise in urbanisation is predicted (Buhaug and Urdal, 2013). One of the main implications of urbanization is air pollution which is associated with several negative health outcomes for urban residents, including respiratory and cardiovascular illness, neurological disorders and cancers (*e.g.* Pope and Dockery, 2006; HEI, 2010). In many urban environments the airborne particulate matter (PM) affects more people than any other atmospheric pollutant and no threshold PM concentration has been identified below which no damage to health is observed (WHO, 2014). It has been estimated that PM causes 3.7 million premature deaths annually worldwide and more than 450,000 in Europe (WHO, 2014). Particulate matter from natural (sea salt, soil dust, volcanic ash, forest fires, pollen) or anthropogenic sources (fuel combustion in thermal power generation, traffic, incineration and domestic heating for households) is directly emitted to the atmosphere (primary) or is formed in air as secondary inorganic or organic aerosols from precursor gases such as SO_2, NO_x, NH_3, and volatile organic compounds. Therefore, the urban PM is a complex mixture of different phases, with different chemical composition and size. Particles with an aerodynamic diameter <10 μm (PM_{10}) can enter the human airways, particles <2.5 μm ($PM_{2.5}$) can reach pulmonary air sacs (Baeza-Squiban et al., 1999) and those <0.1 μm enter the blood circulation system (EEA, 2014).

In cities, the traffic and especially diesel-fuelled vehicles are an important source – close to the ground – of PM-bearing metals and particulate-bound polyaromatic hydrocarbons which have been linked with adverse health effects (*e.g.* HEI, 2010). Non-exhaust emissions (tyre, brake and road surface wear, corrosion and dust re-suspension) from road traffic are about 50% of exhaust emissions of primary PM_{10} and about 22% of the exhaust emissions of primary $PM_{2.5}$ (Hak et al., 2009). Therefore, even with zero tailpipe emissions, the traffic will continue to be a very important source of PM in urban environments (Kumar et al., 2013).

Particles can be removed from the atmosphere by various deposition mechanisms (NEGTAP, 2001), with dry deposition being the main pathway, especially in areas with scarce atmospheric

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precipitation such as the Mediterranean region. Vegetation has a pivotal role in the removal of the atmospheric particulate in terrestrial ecosystems. Dry deposition processes and the particle interception by trees are affected by many factors such the canopy characteristics, wind speed, temperature, particle size, gas solubility as well as leaf pubescence, size and morphology (Beckett et al., 2000; Freer-Smith et al., 2005; Hofman et al., 2014; Weber et al., 2014). Most particles adsorbed on leaves and other plant surfaces are often re-suspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. Although it is well-known that the temporary retention of particles by urban trees can reduce atmospheric PM concentrations (*e.g.* Beckett et al., 2000; Fowler et al., 2004; Nowak et al., 2006) the effectiveness of street trees or vertical gardens as a long-term alternative to other measures such as the wet cleaning of streets is still debated (Litschke and Kuttler, 2008). Some previous quantitative estimates of PM_{10} reduction by urban vegetation on the city-scale suggested a small effect (often <1%; *e.g.* Nowak et al., 2006; Escobedo and Nowak, 2009; Tallis et al., 2011). However, as discussed by Litschke and Kuttler (2008), these estimates assumed a particle deposition velocity (*i.e.* the quotient of the particles' flow rate towards the leaf surface and the atmospheric particle concentration) of about 1 cm s^{-1}, whereas *in-situ* measurements indicate considerably higher values and literature data for PM_{10} deposition velocities to vegetation vary from $\sim$0.01 to $\sim$10 cm s^{-1}. This variability is due to particle characteristics, meteorological conditions as well as to tree species differences in canopy architecture, leaf morphology and surface properties (Pugh et al., 2012; Maher et al., 2013).

Modelling, as well as a number of experimental field and laboratory approaches, have been used to evaluate the PM interception by leaves from a number of plant species (*e.g.* Beckett et al., 2000; Sæbø et al., 2012; Räsänen et al., 2013). It is known that leaf morphology and wettability play an important role in the interception of airborne particles and in their re-suspension to the atmosphere (*e.g.* McPherson et al., 1994). However, limited information is available about the wash-off by rain of adsorbed particles from leaves of different tree species (Neinhuis and Barthlott, 1998).

In order to contribute to the selection and maintenance of tree species with a higher deposition velocity for an efficient PM interception in Italian cities we compared the particle capture and retention capacity by leaves from a popular and prevalent tree species in Italian urban and roadside environments—*Quercus ilex* L., to that of possible alternatives: *Quercus cerris* L., *Platanus* × *hispanica* Münch., *Tilia cordata* Mill., and *Olea europaea* L. In Mediterranean region, the evergreen holm oak (*Q. ilex*) has a wide natural distribution and in Italy it has been used since the sixteenth century in the landscaping of urban and rural parks and gardens. Holm oak has a large canopy, as well as Leaf Area Index (LAI) typically higher than that of other broad-leaf species (Sgrigna et al., 2015); its leaves have a hair cover and thick waxy cuticles. Because of these leaf properties, which enhance the scavenging and retention of airborne particles and the incorporation of lipophilic organic contaminants, holm oak leaves were widely used for biomonitoring persistent pollutants in many Italian urban areas (*e.g.* Monaci et al., 2000; Gratani et al., 2008; Fantozzi et al., 2013; Ugolini et al., 2013). Through a quantitative analysis of PM fractions on *Q. ilex* leaves collected (three times in a year) in an urban environment, Sgrigna et al. (2015) found a mean surface PM deposition of 20.6 μg cm^{-2}, a value in the same range of that reported for other urban tree species by Dzierźanowski et al. (2011). Having in mind the need to diversify planting in order to increase the resilience of urban trees and decrease susceptibility to pests and diseases (Laćan and McBride, 2008), in our study the leaf particle interception and retention by *Q. ilex* were compared with those of other urban tree species to identify possible alternative/complementary trees as PM mitigating tools in Mediterranean urban environments. To evaluate if a cheap and accessible method can produce reliable estimates of tree leaf potential for PM interception, NaCl aerosol and talcum powder were blown onto the leaves in a simple wind tunnel. The results of these laboratory experiments were compared with those from metal particle accumulation in leaves exposed to traffic in an urban street. We chose three metals (Cu, Pb and Zn) routinely associated with anthropogenic pollution sources (Espinosa et al., 2002; Wang, 2006) as indicators of street-level pollution. Tail-pipe emissions, lubricating oils, brake and tyre wear are the main sources of Cu, Pb and Zn in urban air where they are found mainly associated to $PM_{2.5}$ (Egodawatta et al., 2013; Jiang et al., 2015). Direct atmospheric deposition and street dust re-suspension (by wind and traffic turbulences) are the predominant pathways that convey airborne Cu, Pb and Zn to vegetation and other urban surfaces (*e.g.* Gunawardena et al., 2015). Concentrations of these three metals are reported in numerous studies (*e.g.* Davis et al., 2001; Lindgren, 1996), thus enabling baseline comparisons. The leaf particle *retention* capability in the five tree species was also evaluated by simulating a rainfall. Thus, this work attempted to evaluate the agreement among different laboratory experiments and to compare the behaviour of leaves from five selected tree species in terms of particle capture and retention, in the laboratory and the field.

Materials and methods

Plant material

The main leaf characteristics of the five tree species common in Mediterranean urban areas are summarized in Table 1. *P.* × *hispanica* (London plane) has relatively large, stiff leaves coated with fine, firm hairs (during springtime); those of *T. cordata* (lime tree) are also large but mostly hairless, except for small tufts of hair in the leaf vein axils (Hölscher, 2003). Both *Q. ilex* (holm oak) and *Q. cerris* (Turkey oak) leaves have a water-repellent surface mainly due to the thick epicuticular waxy layer. *Q. ilex* is also characterized by stellate trichomes on the surface (Quero et al., 2006). *Olea europea* (olive) has small silvery-green leaves with glossy and veined upper surface (Marchi et al., 2008).

In all experiments, young fully-expanded leaves of the current year's growth were used. Wind-tunnel and laboratory experiments were carried out in Summer 2012 at the University of Reading (UK)

Table 1
Tree species used in the experiment and their leaf properties.

Tree species	Leaf properties			
	Fall/retention	Hairs	Waxes	Size (cm^2)*
Platanus × *hispanica* (London plane)	Deciduous	Yes	Scarce	77.1 ± 4.8
Tilia cordata (Lime tree)	Deciduous	Sparse	Scarce	42.5 ± 4.3
Quercus ilex (Holm oak)	Evergreen	Sparse	Pronounced	14.3 ± 0.9
Quercus cerris (Turkey oak)	Deciduous	No	Pronounced	24.1 ± 2.1
Olea europaea (Olive tree)	Evergreen	Sparse	Pronounced	8.0 ± 0.3

* Average leaf size of experimental leaves.