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Original article

A spatially-explicit method to assess the dry deposition of air pollution by urban forests in the city of Florence, Italy

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ABSTRACT

Urban forests (UF) provide a range of important ecosystem services (ES) for human well-being. Relevant ES delivered by UF include urban temperature regulation, runoff mitigation, noise reduction, recreation, and air purification. In this study the potential of air pollution removal by UF in the city of Florence (Italy) was investigated. Two main air pollutants were considered – particulate matter (PM_{10}) and tropospheric ozone (O_3) – with the aim of providing a methodological framework for mapping air pollutant removal by UF and assessing the percent removal of air pollutant.

The distribution of UF was mapped by high spatial resolution remote sensing data and classified into seven forest categories. The Leaf Area Index (LAI) was estimated spatially using a regression model between in-field LAI survey and Airborne Laser Scanning data and it was found to be in good linear agreement with estimates from ground-based measurements ($R^2 = 0.88$ and RMSE% = 11%). We applied pollution deposition equations by using pollution concentrations measured at urban monitoring stations and then estimated the pollutant removal potential of the UF: annual O_3 and PM_{10} removal accounted for 77.9 t and 171.3 t, respectively. O_3 and PM_{10} removal rates by evergreen broadleaves (16.1 and 27.3 g/m^2), conifers (10.9 and 28.5 g/m^2), and mixed evergreen species (15.8 and 31.7 g/m^2) were higher than by deciduous broadleaf stands (4.1 and 10 g/m^2). However, deciduous forests exhibited the largest total removal due to the high percentage of tree cover within the city. The present study confirms that UF play an important role in air purification in Mediterranean cities as they can remove monthly up to 5% of O_3 and 13% of PM_{10}.

1. Introduction

Cities are major actors in climate change: although they cover less than 2% of the earth's surface, urban areas produce more than 70% of the greenhouse gas emissions that are released into the atmosphere (UN-Habitat, 2011). Ambient air quality in cities may contain high levels of pollutants that cause human health problems (Oakes et al., 2014; Kim et al., 2015; Atkinson et al., 2016). Ground-level concentrations of ozone and particulate matter, which have increased since pre-industrial times in urban and rural regions, are associated with cardiovascular and respiratory mortality and have a significant impact on human and ecosystem health (Paoletti, 2007; Anenberg et al., 2010). Outdoor air pollution kills approximately 8 million people across the world every year (WHO, 2014), with a global cost of 1.7 trillion dollars (OECD, 2014).

Urban forests (UF), defined as the sum of all urban and peri-urban trees, shrubs, lawns, and pervious soils, are key components of Green Infrastructure (GI) (Rouse and Bunster-Ossa, 2013; Lafortezza et al.,

Abbreviations: ALS, airborne laser scanning; BL, height of the boundary layer; ES, ecosystem service; FC, forest category; GI, green infrastructure; GIS, geographical information system; LAI, leaf area index; UF, urban and peri-urban forest

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2013). GI provides a range of ecosystem services (ES) important for human well-being, such as air purification, urban temperature regulation, runoff mitigation, noise reduction and recreation (Bolund and Hunhammar, 1999; Gómez-Baggethun and Barton, 2013; Gómez-Baggethun et al., 2013). UF can reduce air pollutants through a dry deposition process (Hirabayashi et al., 2012; Manes et al., 2012; Nowak et al., 2013; Manes et al., 2016) thanks to the large leaf surface areas of urban trees that act as biological filters, and hence improve air quality (Beckett et al., 1998; Brack, 2002; Nowak, 2006; Sieghardt et al., 2005; Zheng et al., 2013; Grote et al., 2016).

To study the magnitude of air pollution removal by GI, modeling has been used. One of the most used models in urban (Nowak and Crane, 2000; Nowak et al., 2002, 2006) and peri-urban environments (Baumgardner et al., 2012) is i-Tree Eco dry deposition model (former the Urban Forest Effects – UFORE), which has been further developed to enhance i-Tree spatial ability by coupling i-Tree with a Geographical Information System (GIS) (Morani et al., 2011; Hirabayashi et al., 2012; Cabaraban et al., 2013; Nowak et al., 2014).

i-Tree Eco dry deposition model requires meteorological data, pollution concentration, and urban forest structure variables. Hourly meteorological and pollution concentration data are derived from local monitoring stations. Two forest structure variables are needed to assess dry deposition by i-Tree Eco, the amount of canopy cover and its associated Leaf Area Index (LAI, leaf area per square meter projected ground area of canopy). To study forest structure, the sampling protocol for i-Tree Eco foresees that a field sampling is carried out using random or stratified sampling schemes; sample size and plot size of approximately 200 0.04 ha plots per city are recommended (Nowak et al., 2008), though more studies are needed to provide the most accurate estimate of the number of plots (Martin et al., 2013). In each plot, four types of data are collected: general plot information (e.g., land use and tree cover); shrub information (e.g., species, height and cover); ground cover data (e.g., herbaceous cover); and tree information (Nowak et al., 2008). For tree information, i-Tree Eco asks for expensive and time consuming ground measurements, as it requires the following data for each tree inside the plot: species, total height, height to crown base, crown width and percent canopy missing (Escobedo et al., 2008; Nowak et al., 2008; Baumgardner et al., 2012; Barò et al., 2014; Selmi et al., 2016). i-Tree Eco model estimates canopy cover, tree density and LAI using field data, though canopy cover can also be estimated using i-Tree Canopy tool, which allows photo-interpretation of urban land covers from aerial imagery using a sampling approach (Barò et al., 2015). LAI is calculated by i-Tree Eco using regression equations already incorporated into the model or literature data (Baumgardner et al., 2012). However, it is worth noting that i-Tree models the canopy as a whole to get its overall effect and all canopies with the same LAI are treated equally (Selmi et al., 2016). However, because LAI is a relevant variable in pollution deposition, its estimation is an important issue for these types of studies, and the variability of the LAI values based on the amount of leaf area within the study area should be taken into account.

Methods for in situ LAI measurement can be grouped into two main categories: direct and indirect (for a review, see Jonckheere et al., 2004). Direct methods (e.g., destructive sampling or litter traps) are the most accurate, but they are time consuming, and their large scale implementation is not feasible. Indirect methods estimate LAI by observing other, easy to measure variables using optical instruments (e.g., LAI-2000 Plant Canopy Analyzer or hemispherical photography). In urban settings, accurate measurements are hindered by the proximity of trees to infrastructure elements (Chianucci et al., 2005). In addition, LAI is difficult to estimate accurately at landscape scale, especially in heterogeneous vegetation, but different methods have recently been proposed integrating LiDAR (Light Detection And Ranging) data and indirect LAI measurement, such as in conifer (Jensen et al., 2008; Tang et al., 2014; Sumnall et al., 2016) and mixed forests (Richardson et al., 2009; Korhonen et al., 2011; Pope and Treitz, 2013), or digital photographs for isolated trees in urban contexts (Chianucci et al., 2015).

LiDAR is an active remote sensing system based on a laser transmitting short infrared pulses, and a photodiode detecting the backscattered signals. The option mainly exploited to support forestry application is the Airborne Laser Scanning (ALS) based on a LiDAR system mounted on an airplane or helicopter. ALS provides a three dimensional point cloud, which can be used as it is (i.e., point data or waveform) or it can be spatially interpolated to produce the Canopy Height Model (CHM), which provides a measure of the height of the upper canopy in the surveyed area (Corona et al., 2012). ALS data can convey a rich summary of forest features due to their ability to capture the forest heights. For instance, ALS data have been used to: estimate forest height (Magnussen and Boudewyn, 1998; Næsset and Økland, 2002); predict biomass and volume of trees (Næsset, 1997; van Aardt et al., 2006; Corona and Fattorini, 2008); assess vertical stratification of forest vegetation (Zimble et al., 2003; Morsdorf et al., 2010; Ferraz et al., 2012); map tree species composition (Ke et al., 2010; Cho et al., 2012); assess tree size and species diversity (Simonson et al., 2012, 2013; Ozdemir and Donoghue, 2013); classify silvicultural systems, i.e. coppices vs high forests (Bottalico et al., 2014); and assess structural diversity (Mura et al., 2015; Valbuena et al., 2016; Bottalico et al., 2017). However, a few studies have used LiDAR data to predict LAI in UF areas and assess the implication of air pollution removal by GI (Sasaki et al., 2008; Alonzo et al., 2015).

Assessment of air pollution removal by urban GI is still limited for European cities (Tallis et al., 2011; Roy et al., 2012; Selmi et al., 2016), and only a few works have considered European cities in the Mediterranean region (Alonso et al., 2011; Soares et al., 2011; Baró et al., 2014; Baró et al., 2015) where stress factors related to the urban environment co-occur with other limiting factors (e.g., summer drought, high irradiance and temperature) (Fusaro et al., 2015).

In Italy, only few cities have been investigated, mainly Florence (Paoletti, 2009; Paoletti et al., 2011; Bottalico et al., 2016) and Rome (Manes et al., 2012, 2014, 2016; Morani et al., 2014; Fusaro et al., 2015; Silli et al., 2015; Marando et al., 2016; Fares et al., 2016). Among these Italian studies, those based on a spatially approach used other methods than i-Tree Eco model, and were based on forest type maps derived from medium spatial resolution satellite images like the Landsat satellite (Manes et al., 2012, 2014; Silli et al., 2015; Marando et al., 2016) or from the national Corine Land cover map (scale 1:100.000) (Manes et al., 2016), combined with LAI data derived from moderate spatial resolution sensors like MODIS (Bottalico et al., 2016; Manes et al., 2016; Marando et al., 2016). However, such data are not optimal for vegetation studies at the city scale, at least in Mediterranean ecosystems, because of the presence of small forest patches in dense cities like in Florence (Sprintsin et al., 2009). In addition, in urban parks and gardens a large variety of evergreen and deciduous tree species are planted, requiring more than the three/four categories commonly used for their classification in similar studies (conifers, deciduous broadleaves, evergreen broadleaves, and mixed conifers and broadleaves).

In order to reduce the sampling effort when study the spatially-explicit dry deposition capacity of UF, we developed a novel approach for this study, which is based on an integration of different high spatial resolution datasets (remote sensing products and in-field investigations) and GIS analysis. With the city of Florence as a case study, the aims were (1) to provide a methodological framework for mapping the air pollutant removal by UF, and (2) to assess the percent removal of air pollutant by UF, which was not estimated in Bottalico et al. (2016).

The spatial distribution of UF was mapped by remote sensing data and field observations and classified into seven forest categories. We used a spatial model based on LAI data, re-fined by a relationship between in-field LAI survey and ALS-derived metrics in different structural types of UF. We applied pollution deposition equations by using pollution concentrations measured at urban monitoring stations, and then estimated the pollutant removal potential of the UF. Two main air pollutants were considered as they are among the most critical