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Air pollution removal by green infrastructures and urban forests in the city of Florence

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Abstract

We investigated the potential performance of air pollution removal by the green infrastructures and urban forests in the city of Florence, central Italy, with a focus on the two most detrimental pollutants for human health: particulate (PM_{10}) and ozone (O_3). The spatial distribution of green infrastructures was mapped using remote sensing data. A spatial modeling approach using vegetation indices, Leaf Area Index, and local pollution concentration data was applied to estimate PM_{10} and O_3 removal. The results are discussed to highlight the role and potential of green infrastructures and urban forests in improving air quality in Southern European cities.

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Keywords: green infrastructures; urban forests; air quality; ecosystem services; human well-being.

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1. Introduction

Cities are ecosystems: they are open and dynamic systems, which consume, transform and release materials and energy; they develop and adapt; and they interact with humans and with other systemic components. The need to integrate community rights in city landscape strategies and policies while maximizing the environmental benefits essential for human survival and wellbeing, brought to the concept of green infrastructure, i.e. an interconnected network of green spaces that conserves semi-natural and natural ecosystem values and functions and provides associated benefits to human populations. At the conceptual level, Benedict and McMahon (2006) describe Green Infrastructure (GI) as a process-oriented mosaic that "promotes a systemic and strategic approach to land conservation encouraging land use planning and practices that are good for nature and for people." Forests form the backbone of GI and in synergy with rural areas and freshwater, can make ecosystems more healthy and resilient and more effective in providing Ecosystem Services (ES) (Maes et al., 2013). The GI approach has been recently adopted as strategic by the European Commission (COM (2013) 249 final. 2013.) and now is a key step in implementing targets of the European Biodiversity Strategy (Estreguil et al., 2013).

At the urban level, forests and trees can have a pivotal role in providing ES and are the fundamental components of the Urban Green Infrastructure (UGI) (Salbitano et al., 2015). This concept, and the associated strategic, tactical ad operational tools, are capturing an increasing attention in the frame of innovative planning procedures of cities and urban regions (Pauleit et al., 2011). The tree and forest canopy cover in cities, towns, and their surrounding suburbs, supports the quality of life of urban communities and helps local governments achieve environmental, social, and economic sustainability goals. Forest plantations, old forests, street trees, small woodlands and parks, can buffer human settlements from extreme heat and cold, rain and wind, and provide fruit, timber, fuel and employment for a growing population (Sanesi et al., 2011; Conigliaro et al., 2014). Thus, ES provided by urban forests and the related responsibility and payments are emerging topics for the future of the planet. Among the other, a crucial role is played by the potential performance of urban forests and trees in abating the negative effects of a wide range of atmospheric pollutants affecting the health of citizens. Urban forests and trees are excellent filters, indeed they reduce harmful ultraviolet radiation and air pollution, noise and negative sensorial perception. This filtering function contributes in drastically decreasing some direct and indirect negative impacts on human health (Nowak et al., 2014). Besides improving air quality, urban forests and green spaces can also have a positive role on perceived restorativeness and self-reported well-being benefits (Carrus et al., 2015).

2. The role of urban forests in the removal of O_3 and PM

Ground-level concentrations of ozone (O_3) and particulate matter (PM) have increased since pre-industrial times in urban and rural regions and are associated with cardiovascular and respiratory mortality. Anthropogenic $PM_{2.5}$(< 2.5 µm in aerodynamic diameter) causes 3.5 ± 0.9 million cardiopulmonary and 220,000 ± 80,000 lung cancer mortalities (30 ± 7.6 million years of life lost) annually (Anenberg et al., 2010). These figures are possibly under-estimated since the coarse resolution of the global atmospheric model is inadequate to predict urban $PM_{2,5}$ exposures.Tropospheric O_3 is a damaging airpollutant that significantly impacts human andecosystem health (Paoletti, 2007). Ozone is the second most-important air pollutant (after PM) in causing human mortalityand morbidity impacts to human health. Globally,an estimated 0.7 ± 0.3 million deaths per yearare attributed to O_3 pollution, corresponding to 6.3 ± 3.0 million years oflost life (Anenberg et al., 2010).

Due to the potential for improving human health, the role of UGI in the removal of O_3 and PM from the air is a topical subject. Plants also emit biogenic volatile organic compounds (BVOC e.g., isoprene and monoterpenes), that interact with nitrogen oxides (NO_x) to produce O_3 and secondary organic aerosol (SOA). In turn, SOA contributes to PM in the air. These complex chemical interactions occur in the typically heterogeneous urban environment. Several models, e.g. LUR (land use regression) applications (Rao et al., 2014), summarize the present knowledge on vegetation-atmosphere exchanges for estimating the effects of UGI on air quality and human health. One of the most used models is iTree (former the Urban Forest Effects - UFORE) that provides urban forestry analysis and benefits assessment tools, including estimates of UGI effects on air quality (Nowak et al., 2006). By this approach, the total annual air pollution removal by US trees was estimated at 17.4 million tonnes (t) of air pollution in 2010, which saves more than 850 human lives and prevents 670,000 incidents of acute respiratory symptoms a year (Nowak et al., 2014). Globally, effects on human health of the tree-reduced air pollution in the US was estimated at nearly $7 billion saved every year.

The ability ofremoving PM can be affected by tree crown morphology and city design (e.g., city canyon orientation) (Hofman et al., 2013, 2014).In the reduction of air pollutants, an important role is played not only by trees, but also by the structure, texture and localization of green infrastructure components. Alonso et al. (2011) and Baumgardner et al. (2012) highlighted the role ofperiurbanforests for improving air quality by removing ozone and particulate matter in the atmosphere of large metropolitan areas (e.g., Madrid and Mexico City). Also Escobedo et al. (2009) studied the spatial heterogeneity and air pollution removal by urban forests.

A comprehensive analysis of UGI ability in removing O_3 and PM from the air of Florence (Italy) is still missing. Two case studies estimated air pollution removal and BVOC emission in this city (Paoletti, 2009; Paoletti et al., 2011).

Here we investigate the global performance of air pollution removal by the UGI in Florence, (Italy), using remote sensing, spatial modelling and local pollution concentration data. The focus is on the two most detrimental pollutants for human health: particulate (PM_{10}) and ozone (O_3). The aim is to highlight the role and potential of UGI in improving air quality in Southern European cities.

3. Modelling air pollution removal by UGI

Air pollution is removed from the air by three main processes: wet deposition (e.g., transfer of pollutants by falling rain/snow), chemical reactions (e.g., gas phase reactions in the atmosphere), and dry deposition (e.g., transfer of gaseous and particulate pollutants to various surface, including trees) (Rasmussen et al., 1975).Trees remove gaseous air pollution by uptake via leaf stomata, surface deposition and gas-phase reactions following emission of BVOCs. Trees also remove pollution by intercepting airborne particles, which are retained on the plant surface, though the intercepted particles often areresuspended into air or transported to the ground by rain or with leaf and twig fall (Nowak, 1994).Several factors influence dry deposition removal rates by trees, including aerodynamic roughness, pollutant concentration, solar radiation, temperature, turbulence, wind velocity, particle size and vegetation surface characteristics, such as stomatal activity and resistances, and leaf surface area (Sehmel 1980).To study the magnitude of air pollution removal by UGI, computer modeling has been used. Computer simulations have been carried out to investigate air pollution removal from local (e.g., Jim and Chen, 2008; Paoletti et al., 2011), to regional (e.g., Alonso et al., 2011) and continental scale (e.g., Nowak et al., 2014).iTree (former UFORE) is one of the most common models used to get an approximation of the dry deposition system in urban (e.g., Nowak and Crane, 2000; Nowak et al., 2002, 2006) and peri-urban (e.g., Baumgardner et al., 2012) environment. A simplified version of the iTree model has been used to estimate PM_{10} removal in the metropolitan area of Rome (Manes et al., 2014). Other models are the CHIMERE air quality model (Alonso et al., 2011) and the Tiwary method (Tallis et al., 2011), which slightly differ compared to the parametrizations adopted by iTree.The iTree model is based on meteorological, pollution concentration, and urban tree cover data. Meteorological and pollution concentration data are derived from local monitoring stations, while the amount of canopy cover and its associated Leaf Area Index (LAI: m^2 leaf area per m^2 projected ground area of canopy) are the main urban forest parameters used as input variables. Canopy cover is derived from land cover maps or by remote sensing techniques, while iTree estimates LAI using regression equation with field data measurements as input variables.

The pollutant flux to trees is estimated by iTree as the product of dry deposition velocity and hourly pollutant concentration, such that:

$$F = V_d \cdot C \tag{1}$$

where: F = pollutant flux ($g/m^2/sec$); V_d = deposition velocity (m/sec); C = pollutant concentration (g/m^3).

To estimate total pollutant flux to the forests,the pollutant flux (F) is multiplied by the forest cover area A (m^2), over the time period T (sec) for which pollutant concentration is known. These fluxes can be summed to estimate total daily, monthly, or yearly fluxes (Nowak, 1994).Deposition velocity (V_d) for the in-leaf season is estimated by the model using a series of resistance formulas where V_d is described as the reciprocal of resistance to deposition, R_{tot}. R_{tot} is computed as the sum of resistances relating to aerodynamic resistance (R_a), boundary resistance (R_b), and canopy resistance (R_c) (Davidson and Wu, 1990):

$$V_d = \frac{1}{R_{tot}} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \qquad (2)$$

R_a and R_b can be estimated using standard resistance formulas and hourly weather data (Nowak et al., 2006), though R_a is normally considered small compared with the other types and is thus set to zero (Janhäll, 2015). R_c has three components: stomatal resistance (r_s), mesophyll resistance (r_m), and cuticular resistance (r_t), such that:

$$\frac{1}{R_c} = \frac{1}{(r_s + r_m)} + \frac{1}{r_t} \qquad (3)$$

To estimate O_3 removal, r_m is set to 10 sec/m (Hosker and Lindberg, 1982), and r_t is set to 10,000 sec/m (Lovett, 1994). For particulate matter (PM_{10}), which does not directly depend on transpiration and photosynthesis, a median deposition velocity (0.064 m/sec) is considered (Lovett, 1994) based on a LAI of 6 m^2/m^2 and a 50% resuspension rate (Zinke, 1967) and then adjusted to actual LAI. To limit deposition estimates to period of dry deposition, deposition velocities are set to zero during periods of precipitation (e.g., Nowak et al., 2006).

To enhance iTree spatial ability, Hirabayashi et al. (2012) and Caraban et al. (2013) developed a grid-based approach by coupling iTree with a Geographical Information System (GIS) (iTreeEco_D), where input temperature, LAI, and air pollution concentration are spatially distributed, while other meteorological parameters are lumped over the study area. iTreeEco_D model allows the use of input parameters derived from existing spatial database, such as tree cover and LAI values derived from remote sensing products (e.g., Nowak et al., 2014).

4. Potential of Florence UGI for air pollution removal

4.1. Quantifying the urban forest cover in the city of Florence

All natural and semi-natural environmentsin the municipality of Florence were mapped by manual interpretation and GIS delineation of ColourInfraRed (CIR) high resolution aerial orthophotos. We adopted a Minimum mapping Unit (MMU) of 0.5 ha and minimum width of 20 meters. In this study we considered only urban forest areas, following the standard FAO (2010) forest definition which sets a 10% minimum tree crown cover. According to species composition, forest areas were classified as: coniferous, deciduous broadleaved, evergreen broadleaved, mixed broadleaved and coniferous when either broadleaves or conifers did not account for at least the 75% of crown cover (EEA, 2006).

4.2. Meteorological and air quality monitoring in the city of Florence

Meteorological and air quality data are inputs in the iTree model. The WMO weather station of Florence is Peretola (43°48′30.53″N, 11°12′01.46″E, 38 m a.s.l.). The air quality monitoring network (2013)is based on five stations (Table 1). This is a relatively small number of stations compared to the heterogeneity of the climate (Elnahas, 2003) and pollution (Wheeler et al., 2003) across a city. In addition, not allthese air quality stations record all main pollutants (e.g., PM_{10} are recorded at four stations and O_3 at one station). This database, however, may be considered representative for a small-size city like Florence (102 km^2). In Beijing (China), which is 165 times larger than Florence, the role of the urban forests in air pollution reduction was assessed on the basis of modelled meteorological data and air quality data from one single station (Yang et al., 2004). In a detailed investigation over the spatial variability of air pollution removal by urban trees of Santiago (Chile), which is 6 times larger than Florence, modelled meteorological data and eight air quality stations were used (Escobedo and Nowak, 2009).

Table 1. Mean annual value (2013) of PM_{10} and O_3 recorded by the air quality monitoring stations in the city of Florence.

Air pollutant	Air quality monitoring station				
	Fi-Bassi	Fi-Boboli	Fi-Gramsci	Fi-Mosse	Fi-Settignano
PM_{10} (µg/m^3)	20	20	34	30	-
O_3 (µg/m^3)	-	-	-	-	55

4.3. Modelling approach

Temperature, RH and PAR were derived from the meteorological station of Peretola for the year 2013. For O_3 deposition, the parameterization of stomatal uptake developed by UNECE (2014) for Mediterranean evergreen broadleaved forests, deciduous broadleaved forests and conifer forests was applied to the different forest classes and then converted to total O_3 deposition by using the conversion factors in Cieslik (2009).The total amount of PM_{10} removed by each forest class was obtained by integrating the mean monthly pollutant flux over the annual series (Manes et al., 2014):

$$TotalPM_{10}removed = (\sum_{i=1}^{12} V_d \cdot C_i \cdot T_i \cdot 24 \cdot 3600 \cdot LAI \cdot 0.5) \cdot A \quad (4)$$

where: V_d wasset to an average value of 0.0064 m/s based on a LAI = 6 andthen adjusted to actual LAI (Escobedo and Nowak, 2009),C_i is the mean monthlyPM_{10}concentration (g/m^3), T_i is the number of days per month (the time period April-October was considered for deciduous broadleaved), 0.5 is the resuspension rate (Zinke, 1967), and A is the area (m^2) covered by the forest class. LAI data with a spatial resolution of 30 m was estimated for the study area on the basis of the following linear regression (r=0.62) between the Normalized Difference Vegetation Index (NDVI) derived from a Landsat 8 satellite scene acquired on September 9th, 2013, and LAI values at 1-km resolution derived from the level-4 MODIS/Terra leaf area index product (USGS, 2015)on September 6th, 2013:

$$LAI = -2.717593 + 13.948609 \cdot NDVI \quad (5)$$

Removal models for PM and ozone were run for the different forest classes. Results were mapped to provide a detailed distribution of pollutant removal potential of the GI in the city of Florence.

5. Results

Figure 1 shows a map of urban forests in the city of Florence. Urban forests amount to approx. 10% of the total city area. Distribution of these green areas is not uniform. Pollutant removal data from modeling are reported in Table 2. Annual O_3 removal was estimated in 0.023 t/ha for conifers, 0.031 t/ha for evergreen broadleaves, 0.009 t/ha for deciduous broadleaves, 0.021 t/ha for mixed forests.Annual PM_{10} removal was estimated in 0.0204 t/ha for conifers, 0.0176 t/ha for evergreen broadleaves, 0.0152 t/ha for deciduous broadleaves, 0.0247 t/ha for mixed forests.These results are comparable with the results reported byNowak et al. (2006) for US cities, Escobedo and Nowak (2009) for the city of Santiago (Cile), and Manes et al. (2014) for the metropolitan area of Rome (Italy). Figure 2 shows a map of annual pollution removal potentialby GI in the city of Florence. The comparison between O_3 and PM_{10} removal models shows a slightly higher performance for O_3. The highest levels of performance are not related to the urban forest type but depend on the size and continuity of urban forest components.

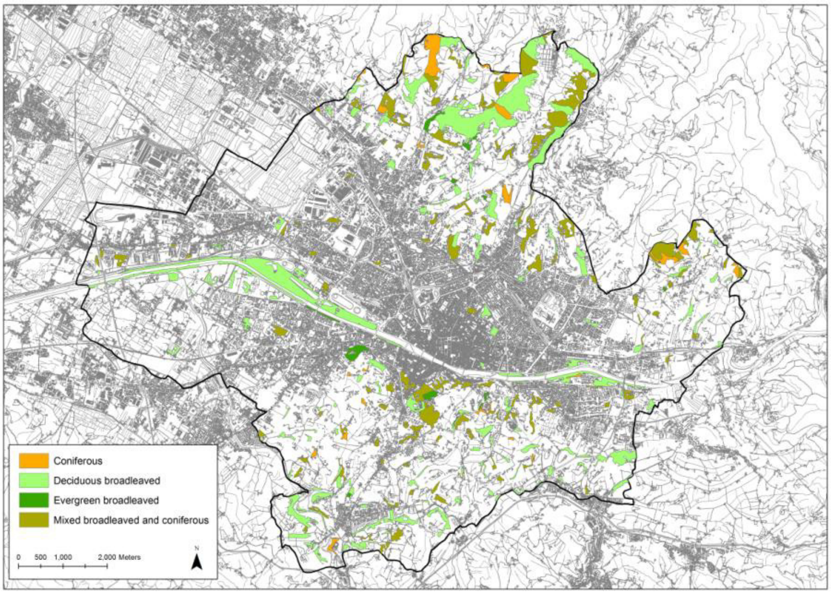

Fig. 1. Distribution of urban forests in the city of Florence.

Table 2. Annual pollution removal (2013) by the urban forests in the city of Florence.

Urban forest type	ha	O_3 (tons/ha)	O_3 (tons)	PM_{10}(tons/ha)	PM_{10}(tons)
Coniferous	73.8	0.0230	1.7	0.0204	1.5
Deciduous broadleaved	595.8	0.0090	5.4	0.0152	9.1
Evergreen broadleaved	29.6	0.0310	0.9	0.0176	0.5
Mixed broadleaved and coniferous	365.3	0.0210	7.7	0.0247	9.0
Total	1064.6		15.7		20.1

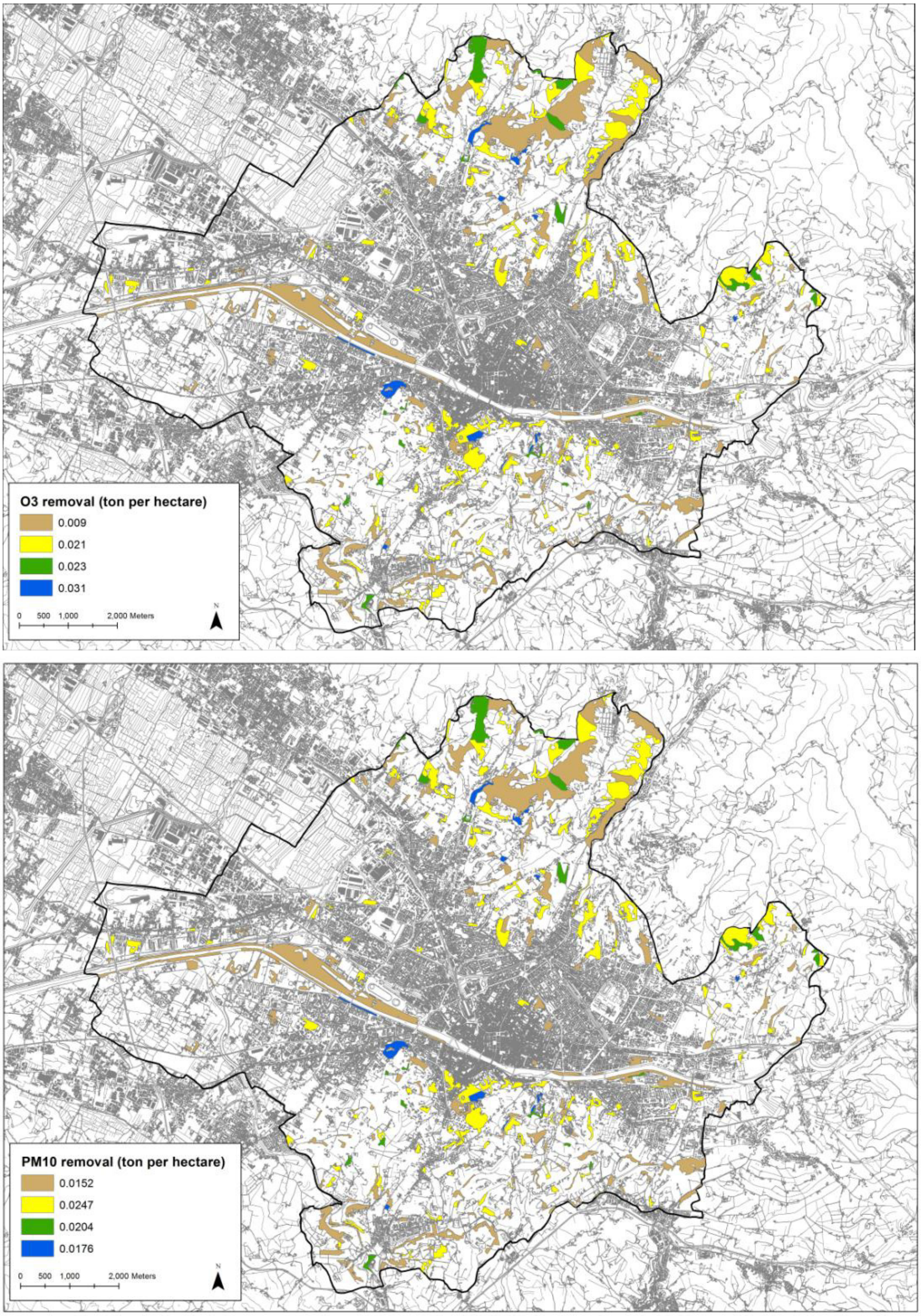

Fig. 2. Distribution of annual (2013) pollutant removal (O_3above and PM_{10}below) by the urban forests in the city of Florence.

6. Discussion and conclusions

Our results show that the estimated contribution of urban forests in abating O_3 and PM_{10} air pollution in the city of Florence is substantial in absolute terms, although relatively modest when compared to overall pollution levels in the city.

The potential effectiveness of urban forests in air quality improvement depends on multiple factors and uncertainties. The city of Florence, with a very densely built center with few green areas and relatively more green surrounding suburbs, suffers from very high pollution levels from car traffic and heating systems. In this situation the role of urban forests in air pollutant removal can be considered marginal, but a more detailed analysis, based on a tighter network of pollutant recording stations, is needed to better evaluate this contribution in the different city areas. In addition, it is worth noting that the contribution of the tree component of GIs is not only limited to the urban forest as described in the present study. Further studies, including other tree components (i.e., street trees, trees in squares, individual and groups of trees in public/private open spaces), need to be assessed in order to improve the efficiency of the model in terms of realistic results of potential removal of PM_{10} and O_3 by the urban forests and trees of Florence.

Finally, the possible role of urban forests in urban air quality improvement must be assessed together with the other positive effects that GIs can have on human well-being.

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