REMOVAL OF AIRBORNE PARTICULATE MATTER BY VEGETATION IN AN URBAN PARK IN THE CITY OF ROME (ITALY): AN ECOSYSTEM SERVICES PERSPECTIVE

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Abstract – Pollution, in particular airborne particulate matter (PM), has been recognized as serious threat to human health. Vegetation may contribute to reduce PM concentration, improving environmental and life quality of inhabitants, especially of those living in urban areas, also delivering important Ecosystem Services to human communities. Here are presented some results of a more extensive research project, aimed to explore the effect of urban vegetation on PM concentrations. The study has been carried out in the year 2012 in Villa Ada, a historical park located north of Rome, surrounded by densely built areas and by high-traffic density roads. An experimental measurements campaign of PM concentrations was conducted. We adopted a simplified model for the estimation of the potential PM_{10} deposition to vegetation. The results showed that trees may effectively abate suspended particles, with evergreen broadleaved trees being most effective in the summer, reducing the average air concentration of PM_{10}. During the year 2012, the woody vegetation of Villa Ada removed in total 4417.2 kg of PM_{10}, and the gross value of this benefit can be estimated as equal to $ 80746. This study confirms the strategic role played by green infrastructures in supporting and improving the provision of important Ecosystem Services in urban areas.

INTRODUCTION

Particulate Matter (PM) is a dangerous air pollutant for human health. Epidemiological studies highlight robust evidences of the link between the increase in airborne PM concentrations, and growing mortality and morbidity for major cardiovascular and respiratory diseases, as well as lung cancer and stroke (Pope et al., 2002; Mannocci et al., 2014). PM in the atmosphere is usually monitored as PM_{10}, including all particles with a size smaller than 10 µm, and $PM_{2.5}$, that includes particles with an aerodynamic diameter smaller than 2.5 µm. The latter represent the most harmful fraction for human health, because their diameter and their

anthropic genesis and the possibility to contain heavy metals and carcinogenic compounds. From the PM aerodynamic diameter depends in fact the particles ability to penetrate into the respiratory system, which acts as a selective filter for different grain sizes of PM: larger particles can reach only the upper respiratory tract, while the breathable fraction includes the fine fraction ($PM_{2.5}$), that can reach the lungs and alveolar regions, as well as the ultrafine fraction (PM_1), capable to enter directly into the blood stream (Perrone et al., 2013 and reference cited therein).
There is, therefore, the urgent need to develop new strategies

to control and abate the environmental concentrations of this pollutant, especially in urban areas, where both pollution concentrations and exposed population are highest (EEA, 2013). At this regard, many studies have confirmed that vegetation can have a relevant role in the amelioration of air quality in urban areas, through its capability to act as a sink for both gaseous and particulate air pollutants (Barò et al., 2014; Song et al., 2015), thus contributing to improve human health and wellbeing (Manes et al., 2008; 2012; 2014; Nowak et al., 2013; 2014). The improvement of air quality is considered as one of the most important Ecosystem Services provided by vegetation in urban areas (Escobedo et al., 2011), and its importance has been demonstrated especially at local level. In particular, urban forest patches such as urban parks and gardens have proven to be effective tools for air pollution mitigation within a city (Cavanagh et al., 2009; Yin et al., 2011; Cohen et al., 2014; Aromolo et al., 2015).

Particles impacting on green surfaces are captured mainly by foliar organs, and rather than being detoxified as for gaseous pollutant, they are re-suspended or washed away by a climatic event (such as wind or rain) (Nowak, 1994, Ould-Dada and Baghini, 2001). The capture ability of the vegetation for the particulate, i.e. the percentage of particles deposited on leaf surfaces in respect to those suspended in the air (Beckett et al., 2000), is related to different factors, many of which belong to the so-called species traits (both morphological and physiological) (Freer-Smith et al., 2005; Sæbø et al., 2012; Nguyen et al., 2015). Among these, the most important are the shape and structure of the leaf blade (smaller leaves with a complex silhouette can capture more PM than larger leaves with regular simple edges), the phyllotaxis and the presence of hairs or epicuticular structures such as waxes, resins or secretion, that may increase the efficiency of retention of the particles on the leaf surfaces (Räsänen et al., 2013; Sgrigna et al., 2014). Even twigs, branches and trunk can capture PM, but in small quantities compared to the foliage. Therefore, grouping vegetation into functional classes such as evergreen broadleaves, deciduous broadleaves and conifers, each one with its intrinsic auto-ecological characteristics and seasonal physiological and phenological dynamics, can help to better understand the effects of urban parks on local air quality, as well as to develop cost effective management strategies aimed to improve the Ecosystem Services provision by urban vegetation.

In previous studies (Manes et al., 2012; 2014), we have estimated the potential capacity of urban trees and periurban forests to reduce air pollution (O_3 and PM_{10}) within the metropolitan area of Rome. Here, by using both a modelling approach and experimental measurements in the field, we have investigated the impact of a large urban park located in the city centre (Villa Ada Savoia) on the local levels of $PM_{2.5}$, PM_{10} and Total Suspended Particles (TSP).

MATERIALS AND METHODS

Study area

The studied area is located inside the Villa Ada urban park, placed in the northern part of Rome, and surrounded by intense traffic roads. Figure 1 shows a map of Villa Ada, obtained by a Landsat 5 TM supervised classification (Manes et al., 2012). This Villa, with a total extension of 160 ha, is one of the largest urban parks in the Rome city centre (Alessio et al., 2002). It is composed by artificial pastures, water bodies and sparse trees, but its inner part is marked by a large forest stand prevalently covered by *Pinus pinea* L. (domestic pine) and *Quercus ilex* L. (holm oak). Deciduous species, such as *Quercus cerris* L. (turkey oak) and *Castanea sativa* Mill. (chestnut) are also present. Table 1 shows the surface cover of each woody vegetation type inside the Villa Ada urban park, while the meteorological conditions recorded inside the Villa during the year 2012 are shown in Figure 2.

Table 1. Surface cover (ha) of the three considered woody vegetation types inside Villa Ada.

Woody vegetation type	Surface cover (ha)
Evergreen broadleaves	38.50
Deciduous broadleaves	35.70
Conifers	42.20
Total	**116.40**

Estimate of potential PM_{10} deposition

In this study, a simplified version of the model presented by Nowak (1994) and Escobedo and Nowak (2009) was applied to estimate the potential PM_{10} deposition to woody vegetation within Villa Ada, in the year 2012:

$$Q = F \times L \times T \tag{1}$$

where Q is the amount of the air pollutant (in our case PM_{10}) removed by trees in a certain time, F is the pollutant flux, L is the total canopy cover in that area, i.e. the Leaf Area Index (LAI, $m^2_{leaf}\ m^{-2}_{soil}$), for each vegetation leaf-type, and T is the time period. The pollutant flux F is calculated as:

$$F = V_d \times C \tag{2}$$

where V_d is the dry deposition velocity of a given air pollutant, and C is its concentration in air. The deposition velocity V_d for PM_{10} was set to an average value of 0.0064 m s^{-1} based on a LAI = 6, and then adjusted to the actual LAI,
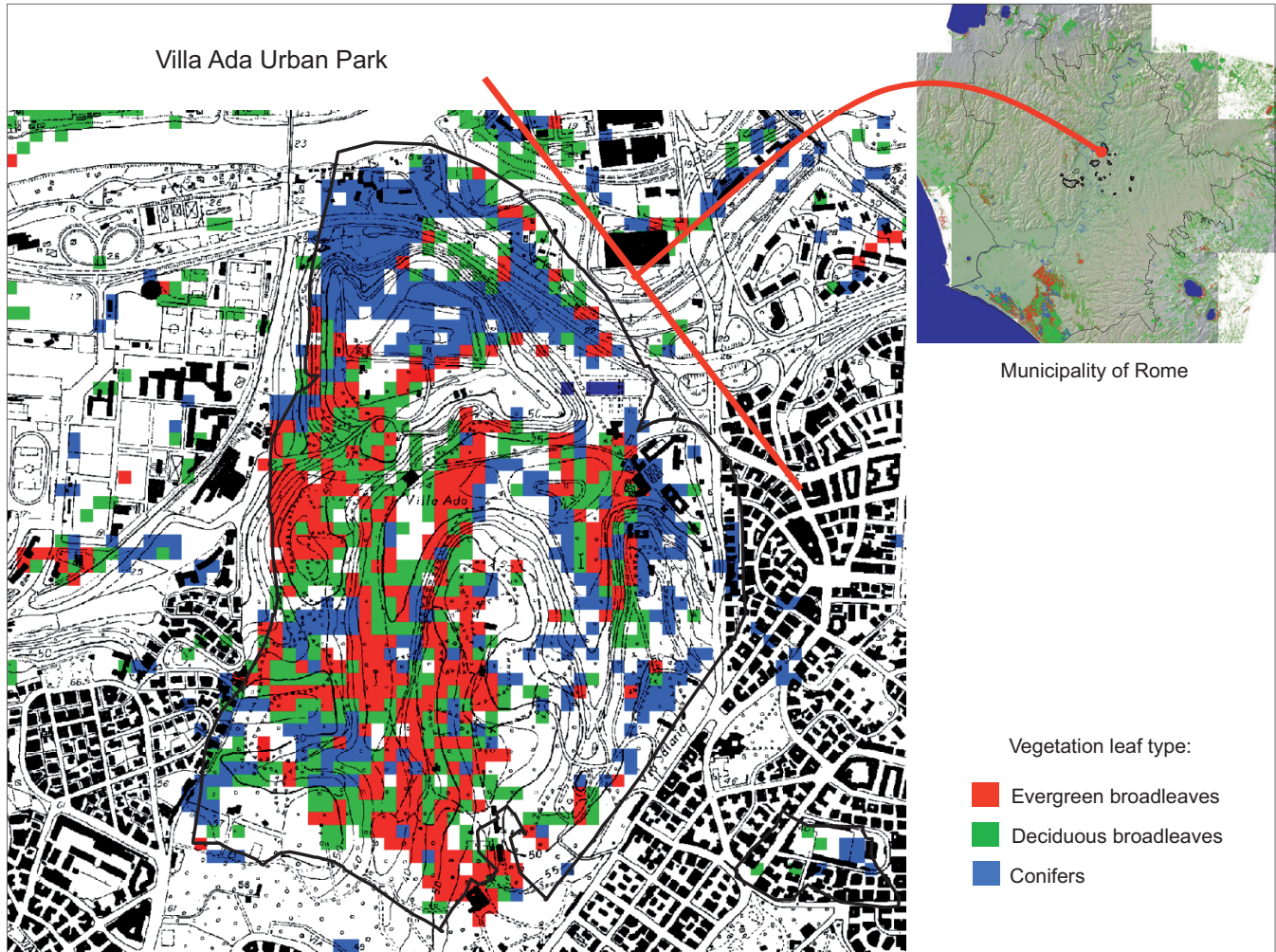
Figure 1. Vegetation map of the Villa Ada Urban Park, and its position inside the Municipality of Rome.

as suggested by Escobedo and Nowak (2009). As for C, the PM$_{10}$ time series (µg m^{-3}) recorded during the year 2012 by the urban background monitoring station of Villa Ada was used. The deposition fluxes where then calculated for each of the three functional groups. The total amount of PM$_{10}$ removed by woody vegetation in 2012 was obtained by integrating the mean daily deposition flux over the annual series as follow:

$$Q_{PM10} = \sum_{i=1}^{365} Vd_i \times C_i \times 24 \times 3600 \times LAI_i \times 0.5 \quad (3)$$

where 0.5 is the resuspension rate of particles coming back to the atmosphere (Zinke, 1967) and LAI$_i$ was the variable used to refer the removal to 1 m^2 of soil covered by the given functional group.

The total amount of PM$_{10}$ removed by woody vegetation in Villa Ada was then estimated by multiplying Q$_{PM10}$ to the total area covered by each vegetation category within the Villa (Manes et al., 2014). The distribution of three functional groups of woody vegetation, namely Evergreen broadleaves (*Quercus ilex* and *Quercus suber* prevalent), Deciduous broadleaves (*Quercus* spp., *Platanus* spp.) and Conifers (*Pinus pinea*) within Villa Ada, has been assessed by using a Landsat 5 TM image (recorded in date 21/07/1999), with spatial resolution of 30 × 30 m. The area covered by each category has been estimated by a Geographic Information System (GIS) analysis, using ESRI ArcGIS software (Table 1). As described in Manes et al. (2012), this information was used to estimate day by day and seasonally, PM$_{10}$ deposition to each functional group. The same method was used for estimating PM$_{10}$ removal simulating as if, in both years, all the trees had belonged to one single functional
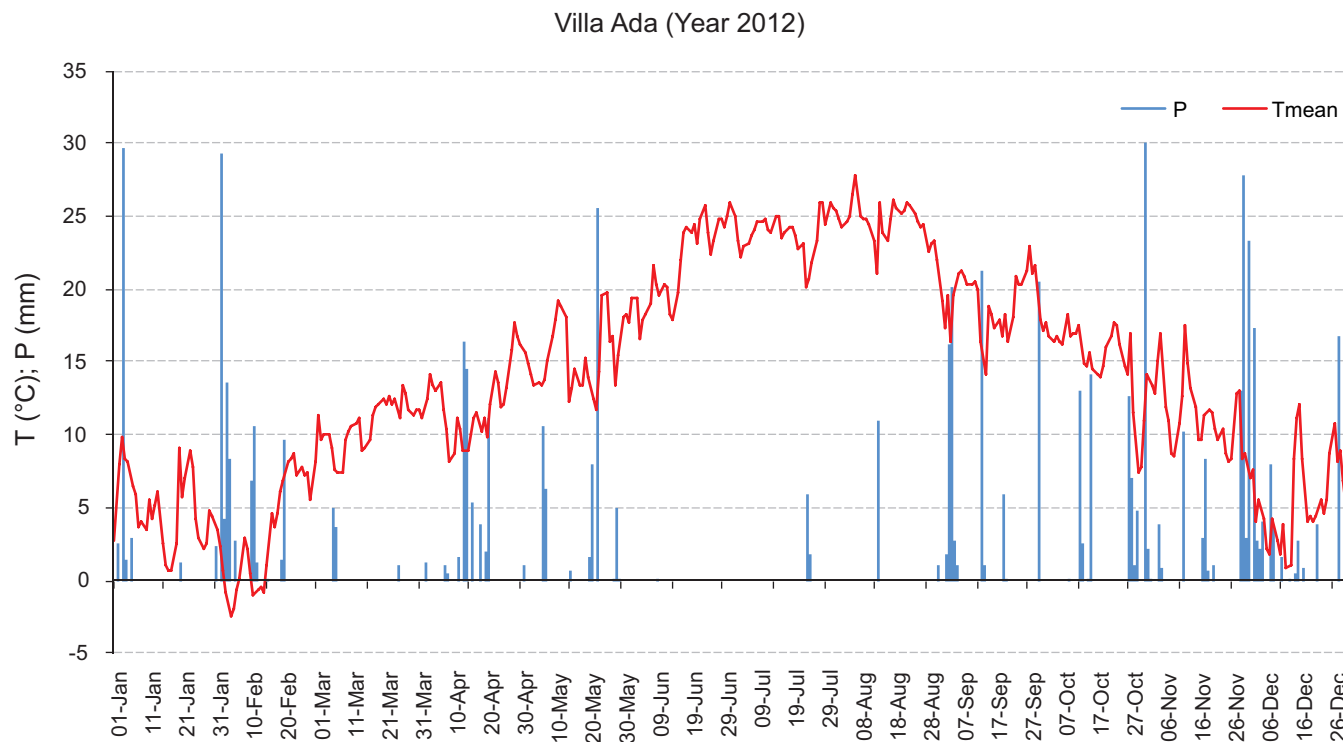
Figure 2. Daily trends of average air temperatures (T, °C) and total precipitations (P, mm), recorded during the year 2012 by the meteorological station located inside Villa Ada (50 m a.s.l.). Data by Arpa Lazio, Regional Centre for Air Quality (http://www.arpalazio.net).

group. In the three scenarios, one for each group, the total area covered by tree vegetation within Villa Ada (116.40 ha) was attributed to each one of them.

Measurements campaigns of $PM_{2.5}$, PM_{10} and TSP

Measurements campaigns were carried out in two sites inside the Villa, "green" site and "bare" site. The "green" sampling site is located in the mixed pine-oak evergreen forest, at approximately 50 m of distance from the main road (SS4 "Via Salaria", about 10,000 vehicles in the 5 rush hours, Alessio et al., 2002), while the "bare" sampling site is located at the same distance from the road, 30 m away from the "green" site on an artificial pasture. In both sites PM measurements were carried out at 1.5 m height from the ground.

The experimental measurement campaign was carried out in the morning and early afternoon (from 10:00 to 14:00 CET) during selected days of 2012 by using optical particle counters (OPC) Aerocet 531 (Metone, USA). These instruments work on light scattering principle (nephelometry) and allow to measure different PM fractions (PM_1, $PM_{2.5}$, PM_7, PM_{10} and Total Suspended Particles, TSP)

simultaneously. Measured values of $PM_{2.5}$, PM_{10} and TSP were corrected for the air water content, by an appropriate equation, depending on relative humidity (Sioutas et al., 2000). Finally, data have been processed, validated, and analyzed by descriptive statistics (Statistica, Statsoft Ltd).

Results and discussion

Estimate of potential PM_{10} deposition

The PM_{10} concentrations in Villa Ada show a typical seasonal trend for the city of Rome, with higher values especially in Winter and Fall (Cattani et al., 2010) (Figure 3). Lower values were instead measured in Spring, when the contribution of domestic heating is missing.

The yearly trend of PM_{10} deposition simulated for the three woody vegetation types (Figure 4) shows that deposition is maximum on evergreen broadleaves and conifers during winter and fall, when deciduous broadleaves do not contribute being in the leaf-off season (Manes et al., 2014). Moreover, deciduous broadleaves show lower deposition values than evergreen broadleaves and conifers, during summer, due to their lower LAI values in the water limited
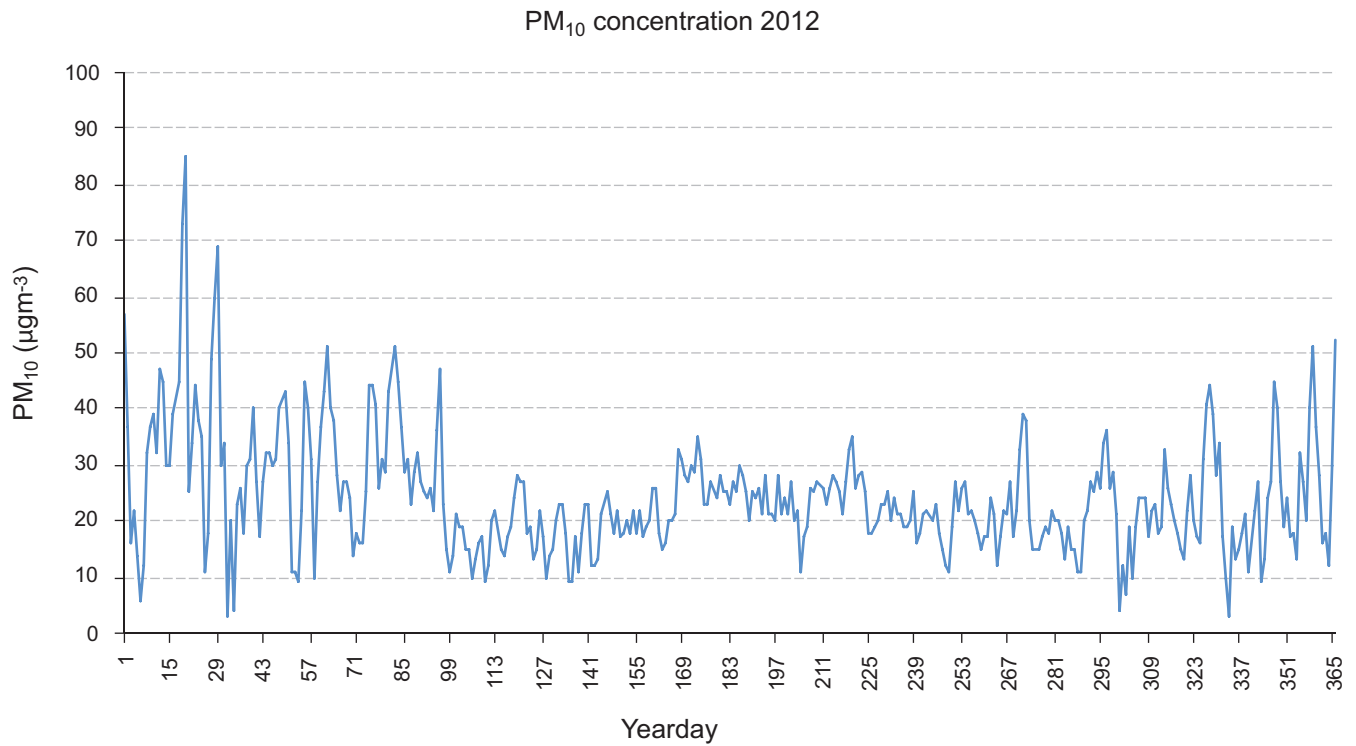
PM$_{10}$ concentration 2012

Figure 3. Daily trend of PM$_{10}$ concentrations measured by the air quality monitoring station of Villa Ada (urban background station) during the year 2012. Data by Arpa Lazio, Regional Centre for Air Quality (http://www.arpalazio.net).

season. The particular water scarcity conditions, affected more the deciduous trees, while the evergreen and conifers vegetation of the Villa show a better adaptation to the drought conditions (Manes et al., 2012).

Table 2 (a, b) summarizes the seasonal cumulated deposition (g m^{-2}) and the total deposition on the whole area covered by

vegetation (116.40 ha), estimated for the year 2012. These values are in agreement with those estimated for the urban and periurban vegetation of the whole Rome Municipality (Manes et al., 2014), as well as with those reported in other cities in different urban areas of the world (Yang et al., 2005; Escobedo e Nowak, 2009). During the year, the highest total
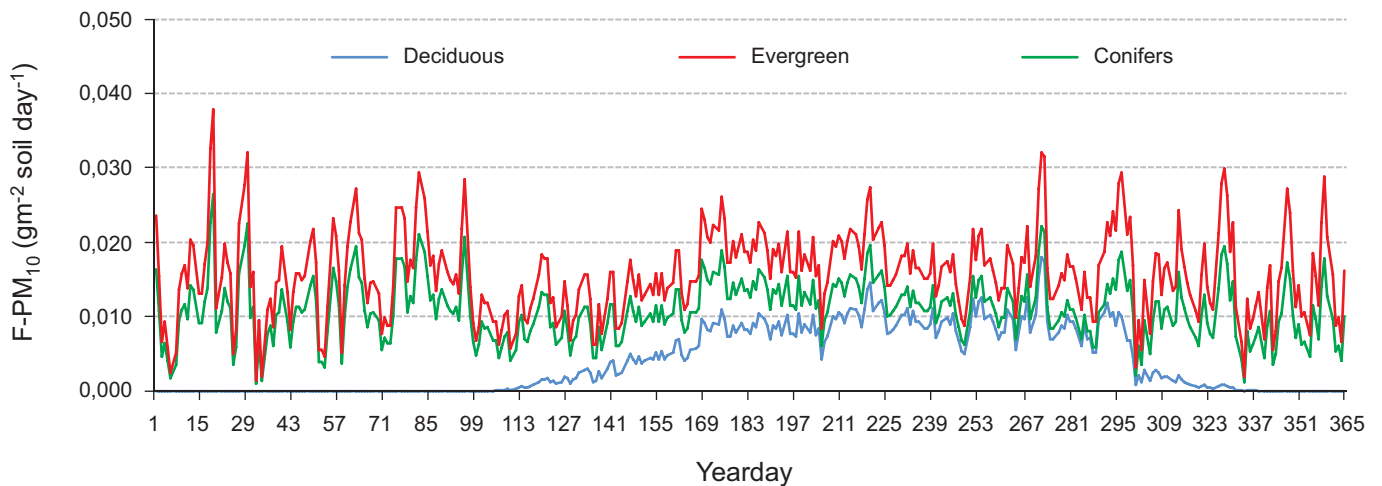

Figure 4. Daily PM$_{10}$ deposition fluxes estimated for Evegreen broadleaves, deciduous broadleaves and conifers on the basis of PM$_{10}$ concentrations reported in Figure 3.

deposition of PM10 was showed by evergreen broadleaves (2213.3 kg), followed by conifers (1692.6 kg) and deciduous broadleaves (511.2 kg). The total PM_{10} removal performed by the three vegetation types altogether was higher during summer (Tab. 2, b), coherently to what was reported by Barò et al. (2014) in a study carried out in the Mediterranean city of Barcelona.

Table 2. a) Seasonal accumulated deposition (g m^{-2}), and (b) total yearly depositions (kg) of PM_{10} estimated for deciduous broadleaves, evergreen broadleaves and conifers in Villa Ada. The total yearly value is based on the vegetation cover reported in Table 1.

a) PM_{10} accumulated seasonal deposition (g m^{-2})

	Evergreen broadleaves	Deciduous broadleaves	Conifers	Mean
Winter	1.418	0.000	1.006	0.808
Spring	1.271	0.294	0.920	0.828
Summer	1.645	0.873	1.176	1.231
Fall	1.414	0.265	0.909	0.863
Year 2012	**5.749**	**1.432**	**4.011**	**3.731**

b) PM_{1} total seasonal deposition (kg)

	Evergreen broadleaves	Deciduous broadleaves	Conifers	Total
Winter	545.8	0.0	424.4	970.2
Spring	489.5	105.0	388.1	982.6
Summer	633.5	311.5	496.4	1441.4
Fall	544.5	94.7	383.7	1023.0
Year 2012	**2213.3**	**511.2**	**1692.6**	**4417.2**

In the Villa Ada Urban park in Rome, we have also simulated the air quality improvement due to vegetation sink capacity for PM_{10} (Figure 5). Four seasonal scenarios for the "real" case (actual vegetation cover for evergreen broadleaves, deciduous broadleaves and conifers), and "no vegetation" (bare soil replacing woody vegetation at all locations), are reported. The ratio vegetation/bare soil depositions was calculated for each vegetation leaf-type. The results show a conspicuous contribution of all the three vegetation leaf-types in removing pollutants from the urban atmosphere. It is interesting to notice, during the particularly dry condition of year 2012, (Figure 2), that evergreen broadleaves were more effective than conifers and deciduous broadleaves in removing PM_{10}.
Millward and Sabir (2011) have quantified the benefits provided by an urban park in Toronto, Canada, in terms of air quality improvement. In particular, these authors have attributed an economic value of $18.28 to each kg of PM_{10} removed by vegetation. According to this work, the Ecosystem Service of PM_{10} removal in Villa Ada during the year 2012 can be valued to $ 9345.3, $ 40459.3 and $ 30941.6 for deciduous broadleaves, evergreen broadleaves
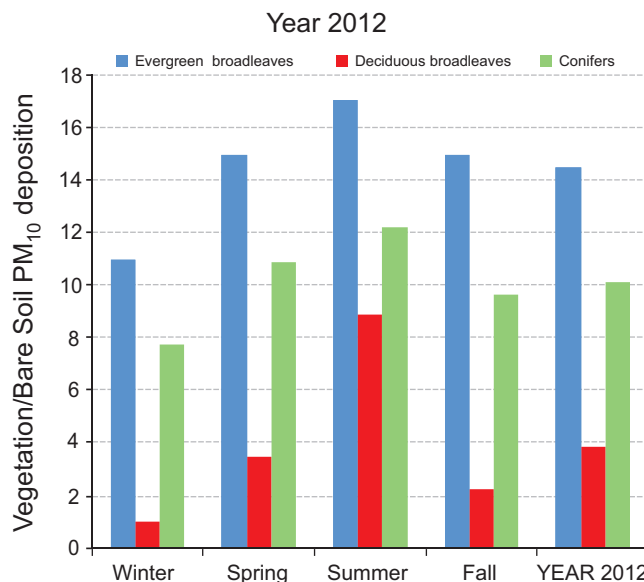

Figure 5. Mitigating role of urban vegetation. Ratio between PM_{10} deposition to each vegetation leaf type ("real case"), and PM_{10} deposition to bare soil ("bare soil scenario"), in the Villa Ada green area (116.40 ha of woody vegetation), during winter, spring, summer and fall 2012.

and conifers, respectively. The benefit of PM_{10} removal provided by the urban trees of Villa Ada in the year 2012 can therefore be estimated as equal to $ 80746.2 in total. This is, however, a gross value, which does not consider the annual costs of managing the urban park and its trees (eg. irrigation, pruning, maintenance), as well as the climatic benefits or the removal of gaseous air pollutants.
Finally, Figure 6 confirms that evergreen broadleaves alone have the highest potential PM_{10} removal (6689.9 kg) followed by conifers (4667.6 kg); both functional types keep their leaves/needles through the whole year, and also during winter, when PM concentrations are highest. In case of the need of increasing the tree cover of an urban park, this functional differences in the Ecosystem Service provision should be taken into account by stakeholders and urban green managers. It is worth noting, however, that in the case in which the vegetation cover of the urban park includes all the three functional types (Real Case), the removal is still high (4417 kg), thus indicating that functional biodiversity plays a crucial role in the provision of the Ecosystem Service of PM_{10} removal, as already highlighted in the case of O_3 removal (Manes et al., 2012).

Experimental campaigns

The trends of the $PM_{2.5}$, PM_{10} and TSP measured in both "green" and "bare" sites (Figure 7, a), showed higher values

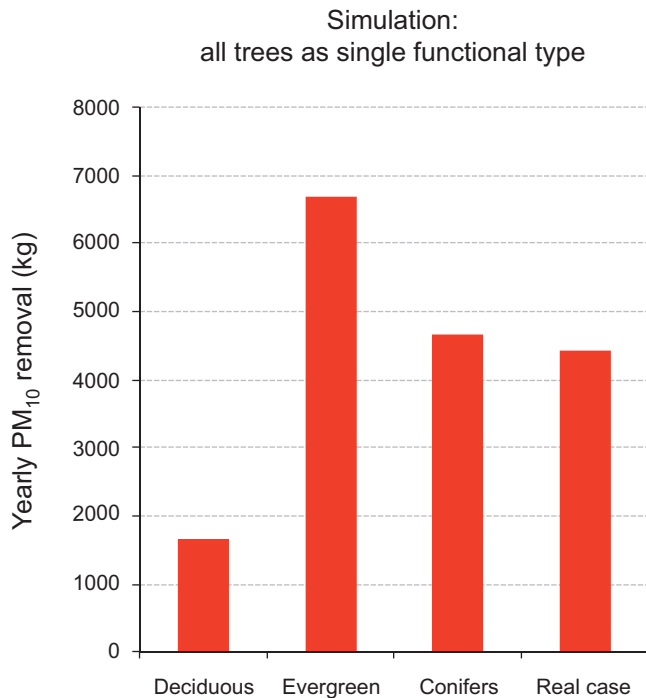## Simulation: all trees as single functional type

Figure 6. Simulation of yearly PM_{10} deposition (kg) that would have occurred in Rome in 2012 if all urban trees would belong to one single functional group.

between 10:00 and 12:00, corresponding to a daily peak of vehicular traffic and related pollutants emissions; it is interesting to note that particles concentration data observed in the "green" area (shrubs and trees) were often lower than those recorded in the "bare" site inside the Villa, characterized by artificial pasture. These results could be explained by the capacity of the woody vegetation in the "green site" to remove PM. However, the contribution of the natural phenomena of deposition and dispersion of PM cannot be considered negligible (Cohen et al., 2014). The average concentrations of PM inside the Villa were, as usually occurs, below the city average values (Cattani et al., 2010; Silli et al, 2014; Fusaro et al., 2015). In particular, $PM_{2.5}$ always showed lower values of concentrations compared to coarser ones (PM_{10} and TSP). This may indicate a contribution to the suspended PM within Villa Ada by soil erosion and biological particles as fungal spores and pollen (Cariñanos et al., 2008).

The highest contribution of vegetation to PM abatement was observed for PM_{10} and TSP (average values: 11.84% and 22.25%, respectively); for these fractions, in fact, it is evident the vegetation flattening effect on the peak concentrations, while the smallest contribution of vegetation was observed in the reduction of the fine fraction $PM_{2.5}$ (2.56%) (Table 3 and Figure 7, b). These results are consistent with those observed from similar studies performed in other major countries in urban parks, as Yin et

al. (2011) in China, whose measured reduction values of the green, between area characterized by trees and shrubs (green) and area without vegetation (bare), in the range of 2 to 35% for the total fraction of PM (TSP).

It is interesting to highlight that the negative values of abatement observed in Figure 7, b, might indicate an emission of dust from the ground, or a re-suspension of particles from plant surfaces caused by wind or other environmental factors present in the site.

Table 3. Average concentration of $PM_{2.5}$, PM_{10} and TSP measured on bare soil (bare) and vegetated soil (green) by using Aerocet analyzers. The average difference (%) of concentration between green and bare for the different PM fraction is also reported.

	$PM_{2.5}$	PM_{10}	TSP
Average concentration bare ($\mu g\ m^{-3}$)	1.54	7.21	10.15
Average concentration green ($\mu g\ m^{-3}$)	1.40	6.23	7.69
Average difference (green vs. bare) (%)	2.56	11.84	22.25

CONCLUSIONS

The results of this research confirm the key role played by the urban forest in supporting and improving the stability of natural systems and of related significant Ecosystem Services, such as the enhancement of air quality, in particular in urban areas. Green infrastructures and their biodiversity, represent therefore a valuable resource to be safeguarded, enhanced and developed, in order to improve the quality of life and of the environment, especially in densely populated metropolitan areas characterized by a high dwelling density.

The estimation of the vegetation effects on PM concentration in natural and urban environments, may be particularly critical, due to the large temporal and spatial environmental variability of all factors that can affect the mechanisms by which the vegetation capture and retains air particulate pollution especially in urban areas. The value of this reduction may be variable and usually higher for the coarse fractions (namely PM_{10} and TSP), while, for the fine ones ($PM_{2.5}$ in particular) the abatement seems to be significantly lower and more related to structure and type of vegetation and by environmental context. The application of numerical models to entire plant communities appears to be a valid option to estimate the potential deposition of PM on vegetation, allowing a comparison with results obtained in studies carried out in other large cities. The obtained data, highlight the ecophysiological response of the three considered types (evergreen broadleaves, deciduous broadleaves and conifers); this may provide particular case studies to build a response scenario in the context of the
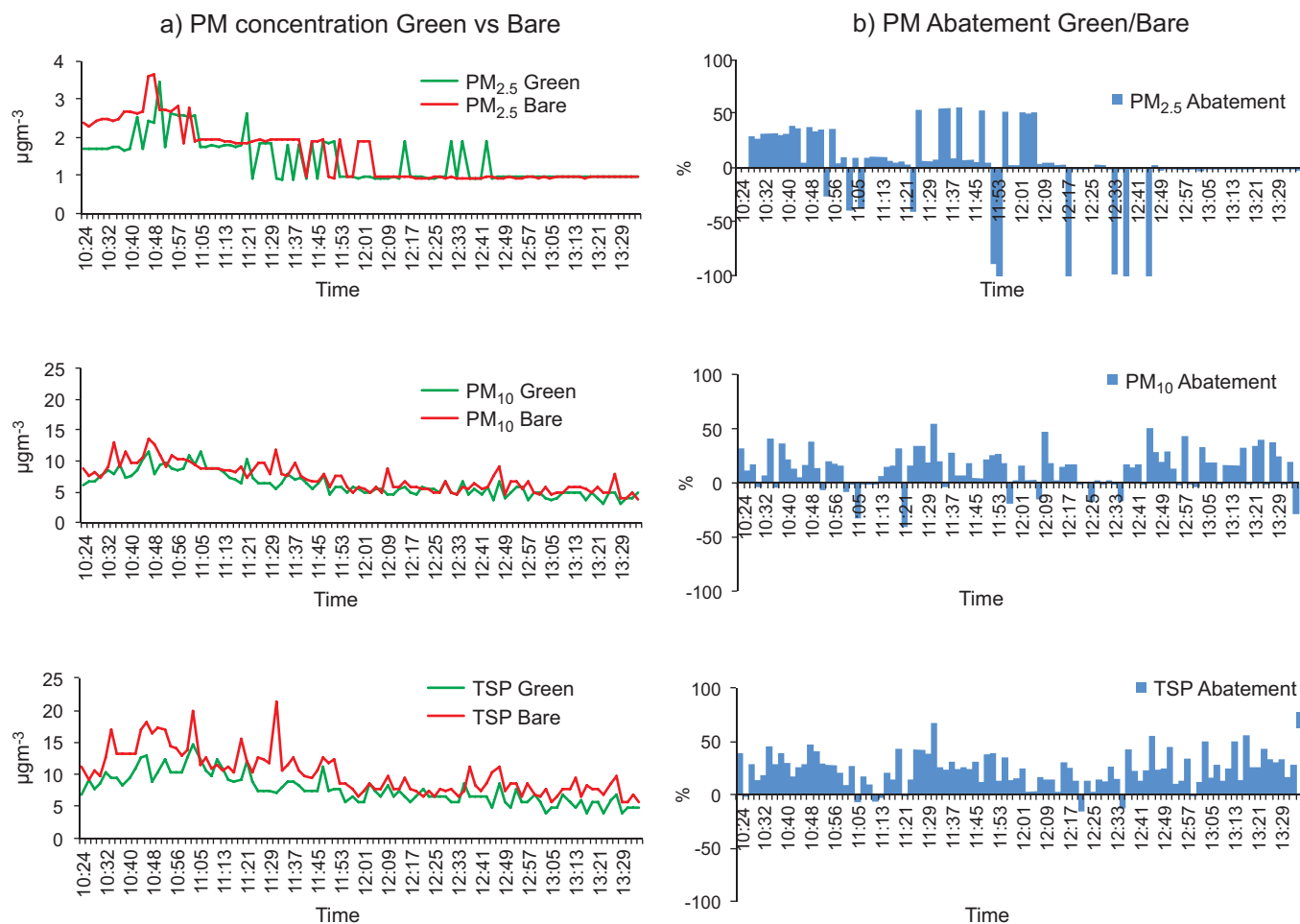
Figure 7. a) Hourly trend of $PM_{2.5}$, PM_{10} and TSP measured in the "green" and "bare" sites in the Villa Ada Urban park; b) the corresponding percentage reduction of PM_{10} concentration of "green" vs "bare" site.

global climate change. Deciduous species seem to be the more vulnerable to the water scarcity and to high temperatures that characterize the summer period in the Mediterranean area, particularly in 2012, compared to the other two types. Evergreen broadleaves instead, being characterized by physiological and morphological adaptations to drought, showed no functional deficits during the dry period, maintaining high values of leaf surfaces (and corresponding high PM abatement). Even conifers have shown a good degree of functional adaptation to summer water stress, but seem to be more sensitive to water reduction, decreasing the production of leaf biomass and consequently decreasing the ability to abate PM_{10}, mainly in the dry season.

However further researches are needed to improve these estimates, and to increase the knowledge for vegetation planning at local scale (Nowak et al., 2013), aiming to minimize human exposure to PM and other harmful pollutants in the urban environment.

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