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# Removal of $PM_{10}$ by Forests as a Nature-Based Solution for Air Quality Improvement in the Metropolitan City of Rome

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**Abstract:** Nature-based solutions have been identified by the European Union as being critical for the enhancement of environmental qualities in cities, where urban and peri-urban forests play a key role in air quality amelioration through pollutant removal. A remote sensing and geographic information system (GIS) approach was applied to the Metropolitan City (MC) of Rome to assess the seasonal particulate matter ($PM_{10}$) removal capacity of evergreen (broadleaves and conifers) and deciduous species. Moreover, a monetary evaluation of $PM_{10}$ removal was performed on the basis of pollution externalities calculated for Europe. Deciduous broadleaves represent the most abundant tree functional group and also yielded the highest total annual $PM_{10}$ deposition values (1769 Mg). By contrast, $PM_{10}$ removal efficiency ($Mg \cdot ha^{-1}$) was 15%–22% higher in evergreen than in deciduous species. To assess the different removal capacity of the three functional groups in an area with homogeneous environmental conditions, a study case was performed in a peri-urban forest protected natural reserve (Castelporziano Presidential Estate). This study case highlighted the importance of deciduous species in summer and of evergreen communities as regards the annual $PM_{10}$ removal balance. The monetary evaluation indicated that the overall $PM_{10}$ removal value of the MC of Rome amounted to 161.78 million Euros. Our study lends further support to the crucial role played by nature-based solutions for human well-being in urban areas.

**Keywords:** urban areas; $PM_{10}$ deposition; urban forests; remote sensing and GIS; tree functional traits

## 1. Introduction

Improving the air quality in cities is one of the main challenges for the European Union (EU). Air pollution due to particulate matter (PM) is considered to represent one of the main health risks for European citizens [1]. A significant proportion of the population in Europe (73%) currently lives in cities, where pollutant concentrations frequently exceed the limits laid down in air pollution regulations. The number of city dwellers is expected to increase to 82% by the year 2050, i.e., 606 million European citizens will live in cities by then. In this regard, in 2011 around 33% of the urban population lived in areas in which the daily air quality limit value for coarse PM ($PM_{10}$) ($50\ \mu g \cdot m^{-3}$ Directive 2008/50/CE) was exceeded, and if the World Health Organization (WHO) annual air quality guidelines ($20\ \mu g \cdot m^{-3}$) are considered, the percentage rises to 88% [1].

This scenario of increasing environmental risks in cities calls for new solutions to improve the quality of urban environments. The European Union recently suggested that the properties of natural ecosystems, and the Ecosystem Services (ES) they provide, may become the focus of specific research and innovation policies in order to find new viable solutions to challenges faced by society [2]. These so-called "nature-based solutions" may exert a positive environmental impact, which could form the basis of sustainable urban planning, by reducing energy requirement costs and mitigating climate changes and the causes of stress conditions [3–5]. As defined in the Millennium Ecosystem Assessment [6], ES are divided in supporting, regulating, provisioning and cultural services, and since biodiversity plays a key role in the provision of ES, it also inevitably affects human well-being [7,8].

In a work aimed at illustrating ES provided by different ecosystems in the city of Stockholm, Bolund and Hunnamar [9] identified seven different urban ecosystems: street trees, lawns/parks, urban forests, cultivated lands, wetlands, lakes/sea, and streams/rivers. Indeed, many papers have highlighted the importance of urban parks and gardens, as well as urban and peri-urban forests, which form an interconnected network of green space known as Green Infrastructure (GI) [10], as providers of different types of ES for urban dwellers [11]. These ES include the improvement in urban microclimate [12,13] and psychological benefits [14], as well as the improvement in air quality [7,15–17], thus integrating conventional human technologies [18]. When Nowak et al. [17] recently analyzed the effects of urban forests on air quality and human health in the United States, they found that the improvement in air quality, measured as a percentage of air pollution removal by trees, accounts for less than 1%. However, in highly vegetated areas, trees can improve air quality by as much as 16% [19]. Baumgardner et al. [20] pointed out that around 2% of the ambient $PM_{10}$ in Mexico City is removed from the study area. In a study carried out in the city of Barcelona (Spain), Barò et al. [21] reported that urban forest services reduce $PM_{10}$ air pollution by 2.66%. Moreover, in the Mediterranean city of Tel-Aviv, Cohen et al. [22] observed that an urban park significantly mitigated nitrogen oxides ($NO_x$) and $PM_{10}$ concentrations, with a greater removal rate being observed in winter, and increased tropospheric ozone levels during summer. The effect of GI on urban air quality thus appears not to be negligible and should be considered in urban planning [23,24]. Indeed, many European cities have a long history not only in the development of the urban fabric, but also in urban green characteristics. In this regard, the major changes that took place in the late 19th century, characterized by rapid urban expansion, largely neglected urban green areas, which means there is now a considerable disparity in the amount of green space available for dwellers in cities across Europe [25]. Within this context, Rome, the capital of Italy, is known to be one of the “greenest” cities in Italy: despite the long-lasting human impact (more than 2750 years) and the marked increase in the urbanized area over the last 60 years, 20% of the overall municipality is still covered by public green areas, which include parks, historical villas, gardens and tree-lined roads, as well as a network of nine natural reserves [26]. Urban forests within the city’s boundaries are composed of residual fragments of ancient woodlands that host a wide range of tree species, such as the typical Mediterranean evergreen broadleaves (*Quercus ilex* and *Q. suber*), deciduous *Quercus* woods (*Q. cerris*, *Q. frainetto*) and conifer plantations (*Pinus pinea*) [7]. There is therefore the need to preserve these existing forests, as well as to improve the urban GI network of Rome, in order to conserve and restore its ES provision, paying particular attention to the effects any initiatives might have on air quality.

The aim of this work was to estimate the seasonal $PM_{10}$ removal capacity of urban and peri-urban forests in the Metropolitan City (MC) of Rome by quantifying the amount of $PM_{10}$ removed by different functional groups of vegetation, i.e., evergreen (broadleaves and conifers) and deciduous forests. We applied a spatially explicit approach, in which the remote sensing of vegetation structure was integrated in the simulation of the $PM_{10}$ deposition fluxes within the different functional groups. Moreover, in order to relate the $PM_{10}$ deposition rates to the varying removal efficiency of the functional groups and to evaluate the $PM_{10}$ removal efficiency of vegetation in a protected area, we present a study case on a peri-urban forest, i.e., the natural reserve of the Castelporziano Presidential Estate. This site is particularly suitable for two reasons: (i) this relatively small area, characterized by the prevalence of forest ecosystems, minimizes the confounding factors deriving from environmental and landscape heterogeneity; and (ii) there is the contemporary presence in this peri-urban forest of all three functional groups of vegetation investigated in this work.

## 2. Materials and Methods

### 2.1. Study Areas: The Metropolitan City of Rome and the Castelporziano Presidential Estate

The MC of Rome, Italy (41°54′ N, 12°29′ E), which corresponds to the former Province of Rome, is one of the 14 Italian MCs, administrative units introduced in 2014 (State Law 56/2014). It covers an area of 5352 km$^2$, which includes extensive and heterogeneous territorial bodies. The MC of Rome, which currently has 4,342,122 inhabitants [27], is characterized by high levels of land use change, accounting for over 50,000 hectares of soil consumption and consisting of a change from non-artificial coverage (non-consumed soil) to artificial coverage (consumed soil), which is defined as the whole sealed and permanently covered surfaces and excludes open natural and semi-natural urban areas [28]. Nevertheless, it also hosts large urban forests and green areas characterized by high levels of natural and historical significance, as well as agricultural areas located within the highly urbanized municipality [29,30]. Beyond the urban inner core of the MC of Rome lie large agricultural surfaces and extensive, heterogeneous forest ecosystems. The MC contains a high degree of biological diversity of tree species found in important natural areas, such as the Regional Park of the Simbruini mountains in the northeast, which is characterized by the widespread presence of deciduous oak species (*Q. cerris*, *Q. frainetto*) and beech woods (*Fagus sylvatica*), the Lepini mountains, which also host typical evergreen broadleaves (*Q. ilex* and *Q. suber*), and the Alban hills in the southeast, where chestnut (*Castanea sativa*) woods prevail, and lastly volcanic mountains (the Tolfa and Sabatini mountains), with mixed broadleaved forests, in its northwestern quadrant. In the southern coastal area of the MC, approximately 20 km from the urban center, lies the Castelporziano Presidential Estate, a natural reserve of around 5900 hectares, characterized by high levels of biodiversity and pristine forests [31,32]. The climate in this estate is strictly Mediterranean and hosts typical Mediterranean ecosystems (Mediterranean maquis, holm oak forests), as well as several deciduous oak communities and pine plantations [33]. Most of the forest cover, which accounts for over 75% of the Castelporziano Presidential Estate, consists of natural or semi-natural forests, many of which are classified as old-growth forest [32].

### 2.2. Classification of Remotely Sensed Data

In order to assess the urban forest composition of the MC of Rome, the Landsat 8 OLI/TIRS image of 18 July 2015, with a resolution of 30 m$^2$, was used to produce a map of the main land use categories. After a radiometric calibration and Dark Object Subtraction, using a semi-automatic Land Cover classification implemented in QGIS [34], a supervised classification was performed, using bands 4, 5, 6 and 7, with a maximum likelihood algorithm. The overall accuracy of the classification was then calculated by means of an error matrix. The physiognomic-structural categories of vegetation identified were then grouped into three main functional groups (evergreen broadleaves, deciduous broadleaves and conifers, Table 1), according to a morpho-functional criterion [7].

**Table 1.** Aggregation scheme of the physiognomic-structural categories of vegetation in the three functional groups.

| Physiognomic-Structural Categories of Vegetation | Functional Groups |
|---|---|
| Conifers prevailing and broadleaved species (*Pinus pinea*, *Quercus* spp.)<br>Reafforestation with Italian stone pine (*Pinus pinea*) | Conifers |
| Holm oak prevailing (*Quercus ilex*)<br>Mediterranean maquis | Evergreen broadleaves |
| Deciduous woods prevailing (*Quercus cerris*, *Q. frainetto*, *Q. pubescens*, *Carpinus* spp.)<br>Chestnut woods (*Castanea sativa*)<br>Beech woods (*Fagus sylvatica*) | Deciduous broadleaves |

### 2.3. Temporal Schedule

All the estimations performed for the MC of Rome were calculated according to astronomical seasons, and by accounting for the different phenology of deciduous and evergreen species. While evergreen deposition was calculated throughout the year, for the deciduous functional group we selected a period of 218 days, from 20 March to 24 October, as the vegetative period, which falls between early spring and early autumn.

### 2.4. Remotely Sensed Leaf Area Index

The Leaf Area Index (LAI) data were retrieved from the Terra Moderate Resolution Imaging Spectroradiometer MODIS MOD15A2H V6 product, with a resolution of 500 $m^2$ and a temporal resolution ofeight days. Forty-six images for the year 2015 were downloaded from the LPDAAC database and georeferenced into the WGS 84 UTM 33N reference system. Low-quality pixels, identified through MODIS quality control, were removed from the images. The images acquired were then aggregated into seasonal means for the year 2015. The number of missing low-quality pixels, removed previously in the cleaning process, was cut by reducing the temporal resolution. In order to obtain spatial consistency between the MODIS LAI data and the land use classification, spatial interpolation of missing LAI pixels, based on a regularized spline tension algorithm, was applied to avoid an incomplete overlay with the classification. Pixels in the LAI data were missing for the following two reasons: (1) the spatial resolution of the MODIS sensor is lower than that of the Landsat classification; and (2) low-quality pixels were removed (cloud contamination, dead detector).

### 2.5. Air $PM_{10}$ Concentrations

Hourly concentrations of particulate ($PM_{10}$) for the year 2015 were obtained from 20 monitoring stations data (Regional Environmental Protection Agency, ARPA Lazio) located throughout the MC of Rome. The monitoring stations, which record $PM_{10}$ concentrations in $\mu g \cdot m^{-3}$, are divided in different classes (Legislative Decree 155/2010) on the basis of their location in the MC (Table 2). Annual mean concentrations for the year 2015 are also shown in Table 2. The seasonal mean concentrations were derived from the hourly $PM_{10}$ concentration data. The point concentrations were then spatialized by means of inverse distance weighting (IDW) interpolation in a GIS environment, which yielded the interpolated values on the basis of both the values of and the distance from the nearby concentration data. Deterministic methods such as IDW have provided good results in interpolating sparse observations, and are widely used in pollution models [35–38].

**Table 2.** Particulate matter ($PM_{10}$) annual mean concentration values and annual range (in $\mu g \cdot m^{-3}$) recorded at the 20 monitoring stations, with the respective class based on the location type within the Metropolitan City (MC) of Rome.

| Monitoring Station | Class | Annual Mean Concentration Value ($\mu g \cdot m^{-3}$) | Annual Range ($\mu g \cdot m^{-3}$) |
|---|---|---|---|
| Francia | Urban traffic | 32 | 84 |
| Magna Grecia | Urban traffic | 31 | 72 |
| Ciampino | Urban traffic | 32 | 117 |
| Fermi | Urban traffic | 31 | 66 |
| Tiburtina | Urban traffic | 34 | 93 |
| Civitavecchia Villa Albani | Urban traffic | 23 | 63 |
| Arenula | Urban background | 29 | 85 |
| Cinecittà | Urban background | 35 | 104 |
| Civitavecchia | Urban background | 20 | 44 |
| Villa Ada | Urban background | 26 | 66 |
| Bufalotta | Urban background | 29 | 78 |
| Cipro | Urban background | 28 | 75 |
| Guidonia | Peri-urban traffic | 28 | 72 |
| Cavaliere | Peri-urban background | 27 | 63 |
| Malagrotta | Peri-urban background | 24 | 65 |
| Colleferro-Oberdan | Industrial/peri-urban background | 30 | 101 |

**Table 2.** *Cont.*

| Monitoring Station | Class | Annual Mean Concentration Value (µg· $m^{-3}$) | Annual Range (µg· $m^{-3}$) |
|---|---|---|---|
| Colleferro-Europa | Industrial/peri-urban background | 34 | 151 |
| Civ. porto | Industrial | 23 | 56 |
| Allumiere | Rural background | 10 | 31 |
| Castel di Guido | Rural background | 22 | 44 |

### 2.6. $PM_{10}$ Deposition

The $PM_{10}$ seasonal concentrations, the LAI MODIS data for the MC of Rome and the surface cover of the three functional groups were used to estimate the amount of $PM_{10}$ dry deposition on vegetation (Figure 1).

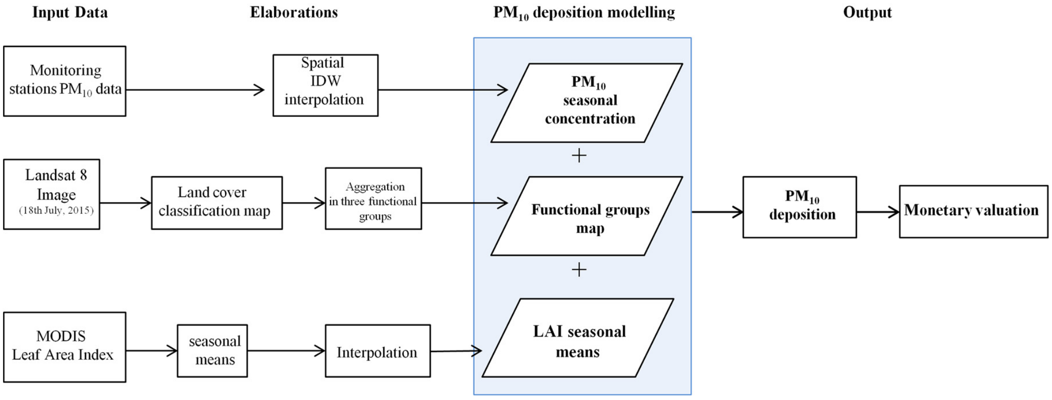

**Figure 1.** Flowchart of the integrated methodology.

Under the assumption of zero rainfall, the downward deposition rate of $PM_{10}$ was calculated according to Nowak's [39] and Yang's et al. [40] methodology. For $PM_{10}$, the deposition velocity was set at a median value of 0.0064 $m \cdot s^{-1}$, based on a LAI mean value of 6 [41], and then adjusted to the actual LAI [42,43]. In order to calculate the total amount (Mg) of $PM_{10}$ removed, the fluxes were multiplied for the surface cover of each functional group.

Lastly, in order to calculate $PM_{10}$ removal per hectare ($Mg \cdot ha^{-1}$), the total amount of $PM_{10}$ was normalized for the surface area of the respective functional group.

### 2.7. Monetary Evaluation

The monetary value of $PM_{10}$ reduction provided by the functional groups was estimated by using the externality value (cost per Mg) of $PM_{10}$ pollution. Externalities can be described as the estimated social cost of pollution (i.e., human health, environmental impact and material damage) that is not considered in the market price of the goods or services that caused the pollution [19]. By applying the externality value calculated for the European context for $PM_{10}$, which has been previously used in European environmental policies and programs [44,45], we calculated the monetary value for the amount of $PM_{10}$ removed. This value corresponds to 22,990 Euros per Mg, and is calculated on the basis of the value of a life year (VOLY). This value represents the cost to society of the damage caused by pollution to people's health and the environment [46].

## 3. Results

### 3.1. Land Cover Map of the Metropolitan City of Rome

Figure 2A shows the land cover map of the Metropolitan City of Rome obtained by classifying a Landsat 8 OLI/TIRS image (18 July 2015).

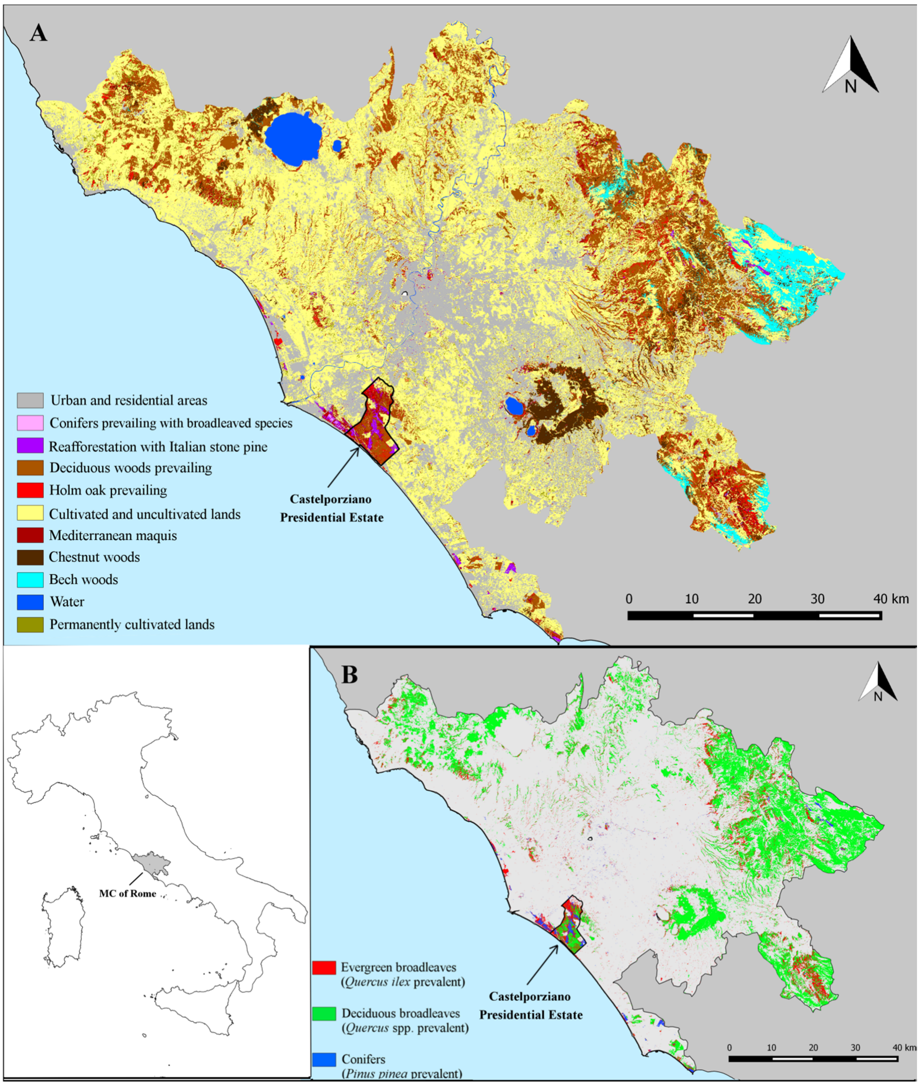

**Figure 2.** (**A**) Land cover classification of the Metropolitan City (MC) of Rome (18 July 2015 Landsat 8 OLI/TIRS image); (**B**) Map of the three functional groups obtained by means of a morphofunctional aggregation of the physiognomic-structural categories of vegetation of the MC of Rome (see text for further details).

This map, which has an overall classification accuracy of 95.6%, reveals a complex mosaic of 11 different land use classes, seven of which are natural ecosystems with heterogeneous structural and functional traits. The areas covered by cultivated and uncultivated lands and by permanently cultivated lands are also shown, as are urban and residential areas. The main land use types in the MC of Rome are cultivated and uncultivated lands (55%), followed by urbanized and residential areas (22%), while natural ecosystems cover the remaining 22% of the MC.

Figure 2B shows the map of the three vegetation functional groups obtained by means of a morphofunctional aggregation of the woody vegetation of the MC of Rome. Worthy of note is the fact that deciduous broadleaves are the most abundant functional group in the MC (92,927 ha), followed by evergreen broadleaves (21,116 ha) and conifers (2950 ha). The most abundant functional group in the Castelporziano Estate is that of the evergreen broadleaves (2017.53 ha), followed by deciduous broadleaves (1887.84) and, lastly, by conifers (750.06).

### 3.2. *LAI and $PM_{10}$ Removal Efficiency by Vegetation in the MC of Rome*

The LAI values yielded by dense evergreen forests, as well as by large natural and biodiverse areas such as the Castelporziano Presidential Estate in the southern coastal area of the MC, are high throughout the year (Figure 3), peaking in summer (up to ~6.7 $m^2 \cdot m^{-2}$) before gradually dropping to a minimum in winter.

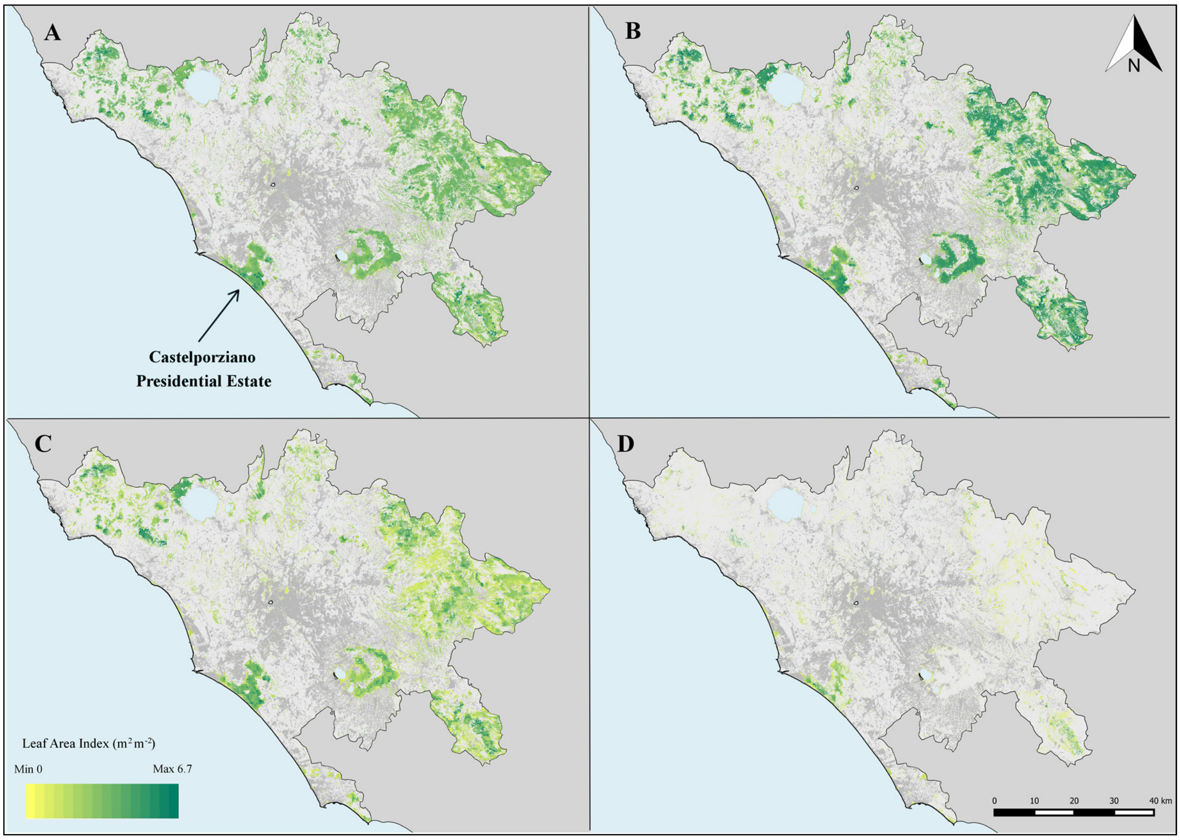

**Figure 3.** Maps of the seasonal Leaf Area Index (LAI, $m^2 \cdot m^{-2}$) ((**A**) spring; (**B**) summer; (**C**) autumn; (**D**) winter). The autumn LAI values for the deciduous broadleaves shown in panel (**C**) were calculated until 24 October.

The spatial distribution of $PM_{10}$ seasonal deposition rates per surface unit ($g \cdot m^{-2}$) (Figure 4) follows a similar pattern to that of the LAI values. Spring $PM_{10}$ deposition rates in most of the MC (Figure 4A) range approximately from 0.5 to 7.7 $g \cdot m^{-2}$, increasing in the summer months (Figure 4B). The highest values (up to around 9 $g \cdot m^{-2}$) were recorded in the northeastern quadrant of the MC, which is characterized by the widespread presence of deciduous forest stands, whereas lower values are concentrated in the northwestern quadrant of the MC, where $PM_{10}$ concentrations are minimal (data not shown). Autumn deposition values (Figure 4C) are generally lower, presenting, however, peaks of around 12 $g \cdot m^{-2}$ found close to the Castelporziano Estate and in the evergreen broadleaved forests in the southeastern quadrant of the MC. The winter months (Figure 4D) yield lower annual values, though peaks of around 7 $g \cdot m^{-2}$ were recorded in evergreen forest stands in the southeastern quadrant of the MC and in the Castelporziano Presidential Estate. The highest mean LAI values for all three functional groups were observed in summer, with values for deciduous broadleaves ($3.84 \pm 1.31$ $m^2 \cdot m^{-2}$) being followed by evergreen broadleaves ($3.04 \pm 1.37$ $m^2 \cdot m^{-2}$) and conifers ($2.65 \pm 1.35$ $m^2 \cdot m^{-2}$) (Table 3), whereas the lowest were observed in winter ($1.26 \pm 0.83$ $m^2 \cdot m^{-2}$ for evergreen broadleaves and $1.54 \pm 1.11$ $m^2 \cdot m^{-2}$ for conifers). Deciduous broadleaves yielded higher mean LAI values throughout the vegetative period than the other two functional groups.

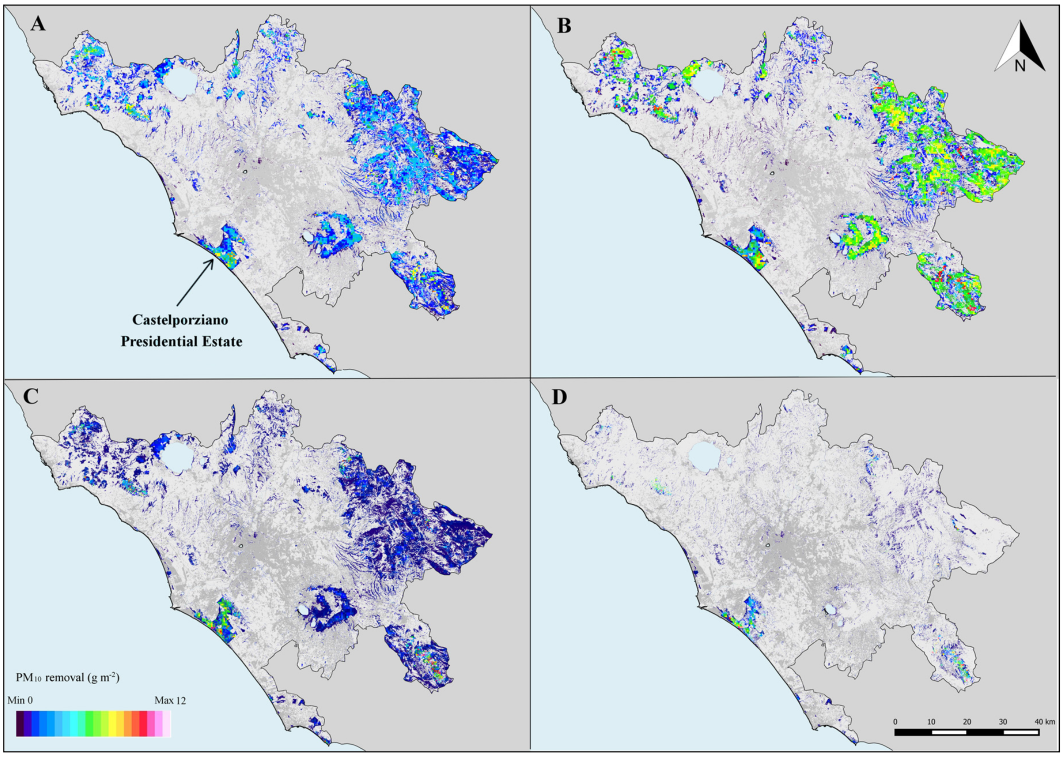

**Figure 4.** Seasonal particulate matter ($PM_{10}$) deposition maps ($g \cdot m^{-2}$) estimated for the three functional groups in the MC of Rome ((**A**) spring; (**B**) summer; (**C**) autumn; (**D**) winter). The autumn deposition values on the deciduous broadleaves shown in panel (**C**) were calculated until 24 October.

**Table 3.** Seasonal $PM_{10}$ concentrations ($\mu g \cdot m^{-3}$) and Leaf Area Index (LAI) value ($m^2 \cdot m^{-2}$), calculated for the three functional groups in the MC of Rome. Data are means ± standard deviation.

| | **Mean $PM_{10}$ Concentrations ($\mu g \cdot m^{-3}$)** | | | **Mean LAI ($m^2 \cdot m^{-2}$)** | | |
|---|---|---|---|---|---|---|
| | **Deciduous** | **Evergreen** | **Conifers** | **Deciduous** | **Evergreen** | **Conifers** |
| **Spring** | 23.19 ± 1.04 | 23.18 ± 1.10 | 23.47 ± 0.91 | 3.22 ± 0.76 | 2.92 ± 0.94 | 2.58 ± 1.01 |
| **Summer** | 24.49 ± 0.32 | 24.34 ± 0.67 | 24.23 ± 0.83 | 3.84 ± 1.31 | 3.04 ± 1.37 | 2.65 ± 1.35 |
| **Autumn** | 20.00 ± 1.71 * | 34.24 ± 6.15 | 33.54 ± 3.95 | 2.33 ± 1.04 * | 1.88 ± 1.04 | 2.00 ± 1.20 |
| **Winter** | | 33.79 ± 7.54 | 32.71 ± 4.81 | | 1.26 ± 0.83 | 1.54 ± 1.11 |

* Autumn mean values for deciduous broadleaves were calculated until 24 October.

The total annual $PM_{10}$ deposition calculated for the three functional groups (in Mg, Table 4) is higher for deciduous broadleaves (5573.86 Mg), and lower for evergreen broadleaves (1293.16 Mg) and conifers (169.88 Mg), which reflects the extent of their surface cover. Table 4 also shows the total and seasonal $PM_{10}$ removal efficiency of each of the three functional groups (in $Mg \cdot ha^{-1}$). Most of the $PM_{10}$ removal by the three functional groups (both as total, in Mg, and in $Mg \cdot ha^{-1}$) occurs in the summer months (3213.52, 489.85, and 54.03 Mg and 0.035, 0.023, and 0.018 $Mg \cdot ha^{-1}$ for deciduous broadleaves, evergreen broadleaves and conifers, respectively), with minimum removal being observed in winter. Total efficiency is comparable for all three functional groups (0.060, 0.061, and 0.058 $Mg \cdot ha^{-1}$ for deciduous broadleaves, evergreen broadleaves and conifers, respectively). The monetary evaluation of the ES of $PM_{10}$ removal yields an overall value of 161.14 million Euros for all the urban and peri-urban forests in the MC of Rome.

**Table 4.** Seasonal $PM_{10}$ deposition (total, Mg, and per hectare, as $Mg \cdot ha^{-1}$) and related monetary value (in Euros) calculated for the three functional groups in the MC of Rome.

| | **Deciduous** | | | **Evergreen** | | | **Conifers** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** |
| **Spring** | 2008.56 | 0.022 | 46.18 | 392.94 | 0.019 | 9.03 | 45.48 | 0.015 | 1.05 |
| **Summer** | 3213.52 | 0.035 | 73.88 | 489.85 | 0.023 | 11.26 | 54.03 | 0.018 | 1.24 |
| **Autumn** | 351.78 * | 0.004 * | 8.09 | 278.26 | 0.013 | 6.40 | 43.57 | 0.015 | 1.00 |
| **Winter** | | | | 132.11 | 0.006 | 3.04 | 26.80 | 0.009 | 0.62 |
| **Total** | 5573.86 | 0.060 | 128.14 | 1293.16 | 0.061 | 29.73 | 169.88 | 0.058 | 3.91 |

* Autumn mean values for deciduous broadleaves were calculated until 24 October.

### *3.3. Study Case: Contribution of Castelporziano Presidential Estate Peri-Urban Forest to Air Quality Improvement*

Table 5 shows the mean LAI and $PM_{10}$ concentrations for the peri-urban forest of the Castelporziano Presidential Estate. $PM_{10}$ concentrations are very homogeneous between the three functional groups within the Castelporziano Presidential Estate (mean value of approximately 23 and 24 $\mu g \cdot m^{-3}$ in spring and summer, respectively, for all the functional groups), and as an annual mean value (29.29 ± 0.18, 29.29 ± 0.16, 29.22 ± 0.19 for conifers, deciduous broadleaves and evergreen, respectively). The deciduous broadleaves' mean LAI was higher than that of evergreen broadleaves and conifers, particularly in summer (4.25 ± 1.11 $m^2 \cdot m^{-2}$). The LAI values in the Castelporziano Estate for the three functional groups were generally higher throughout the year than those estimated for the whole MC of Rome.

**Table 5.** Seasonal $PM_{10}$ concentrations ($\mu g \cdot m^{-3}$) and LAI value ($m^2 \cdot m^{-2}$), calculated for the three functional groups in the Castelporziano Estate. Data are means ± standard deviation.

| | **Mean $PM_{10}$ Concentrations ($\mu g \cdot m^{-3}$)** | | | **Mean LAI ($m^2 \cdot m^{-2}$)** | | |
|---|---|---|---|---|---|---|
| | **Deciduous** | **Evergreen** | **Conifers** | **Deciduous** | **Evergreen** | **Conifers** |
| **Spring** | 23.58 ± 0.13 | 23.52 ± 0.14 | 23.57 ± 0.14 | 3.88 ± 0.91 | 3.49 ± 0.93 | 3.50 ± 0.77 |
| **Summer** | 24.23 ± 0.12 | 24.16 ± 0.13 | 24.22 ± 0.13 | 4.25 ± 1.11 | 3.56 ± 1.17 | 3.63 ± 0.97 |
| **Autumn** | 19.53 ± 0.21 * | 32.37 ± 0.50 | 32.49 ± 0.46 | 3.99 ± 1.12 * | 3.05 ± 1.02 | 3.46 ± 0.90 |
| **Winter** | | 30.95 ± 0.54 | 31.11 ± 0.51 | | 2.13 ± 0.89 | 2.63 ± 0.84 |

* Autumn mean values for deciduous broadleaves were calculated until 24 October.

Table 5 shows the $PM_{10}$ removal values calculated for the three functional groups within the Castelporziano Presidential Estate. Spring and summer removal rates (in $Mg \cdot ha^{-1}$) are higher for deciduous broadleaves (0.032 and 0.040 $Mg \cdot ha^{-1}$); nevertheless, evergreen broadleaves and conifers display high removal rates even in autumn (0.028 and 0.034 $Mg \cdot ha^{-1}$, respectively), and lower removal rates in winter (0.013 and 0.019 $Mg \cdot ha^{-1}$, respectively). As a result, the total $PM_{10}$ removal capacity is higher for evergreen broadleaves and conifers (0.10 and 0.11 $Mg \cdot ha^{-1}$) than for deciduous broadleaves (0.08 $Mg \cdot ha^{-1}$). Table 6 also shows that $PM_{10}$ removal by the peri-urban forest of the Castelporziano Presidential Estate yields an overall value of 10.44 million Euros.

**Table 6.** Annual $PM_{10}$ deposition (total, Mg, and per hectare, as $Mg \cdot ha^{-1}$) and related monetary value, calculated for the three functional groups in the Castelporziano Estate.

| | **Deciduous** | | | **Evergreen** | | | **Conifers** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** | **Mg** | **$Mg \cdot ha^{-1}$** | **Value (€ $10^6$)** |
| **Spring** | 60.74 | 0.032 | 1.40 | 53.18 | 0.026 | 1.22 | 19.48 | 0.026 | 0.45 |
| **Summer** | 75.90 | 0.040 | 1.75 | 58.87 | 0.029 | 1.35 | 22.02 | 0.029 | 0.51 |
| **Autumn** | 18.68 * | 0.010 * | 0.43 * | 56.06 | 0.028 | 1.29 | 25.80 | 0.034 | 0.59 |
| **Winter** | | | | 27.18 | 0.013 | 0.62 | 14.55 | 0.019 | 0.33 |
| **Total** | 155.32 | 0.08 | 3.57 | 195.28 | 0.10 | 4.49 | 81.85 | 0.11 | 1.88 |

* Autumn mean values for deciduous broadleaves were calculated until 24 October.

## 4. Discussion

The $PM_{10}$ deposition values obtained for the year 2015 are comparable to those reported in previous studies performed in the Metropolitan City of Rome [15,16,47]. Manes et al. [16] also previously investigated the role played by GI in $PM_{10}$ abatement in 10 MCs of Italy for the year 2003. The removal values reported previously are slightly lower than those that emerge from this study, though it should be borne in mind that 2015 was characterized by intense episodes of $PM_{10}$ pollution, with almost 35 days in which air pollutant concentrations exceeded the threshold of 50 $\mu g \cdot m^{-3}$ in the city of Rome, which is the limit imposed by the Italian government (Legislative Decree 155/2010) for the protection of human health [48], whereas $PM_{10}$ air concentrations modeled for the year 2003 were generally lower. What emerges from this study is the elevated efficiency of deciduous species in $PM_{10}$ removal during the spring and summer months resulting from a higher LAI: the evaluation of the seasonal $PM_{10}$ removal trend showed that deciduous broadleaves are the species that most effectively removes $PM_{10}$ from the atmosphere during the vegetative period, which is in keeping with their phenology. Indeed, as expected, the data yielded both by the MC of Rome and the Castelporziano Presidential Estate showed that the summer $PM_{10}$ removal rates are higher. This finding is in agreement with those of Silli et al. [47], who reported a $PM_{10}$ removal peak during the summer season and differences in the $PM_{10}$ removal capacity between the three functional groups in an urban park in the center of Rome. Nevertheless, the Castelporziano study case allowed us to more accurately define the varying removal capacity of the three functional groups in a territory characterized by relatively homogeneous environmental conditions. If we consider the total removal values of the three functional groups in the Castelporziano study case, what emerges is the importance for $PM_{10}$ abatement of evergreen species, as also showed in an experimental study performed in an evergreen broadleaved urban forest [49]. Indeed, we observed that the total annual $PM_{10}$ removal efficiency of evergreen species (evergreen broadleaves and conifers) is 20% to 27% higher than that of deciduous broadleaves on an annual scale. This suggests that evergreen communities have a greater impact on air quality amelioration on a year-long basis. Furthermore, since $PM_{10}$ pollution levels usually rise in winter [49–51], we presume that increasing evergreen species cover in highly polluted areas would, given the ability of such species to abate pollutant levels throughout the year, help to prevent or mitigate pollution peaks. It is noteworthy that although the estimated mean $PM_{10}$ air concentrations in the MC of Rome are not markedly different from those in the Castelporziano Presidential Estate, the latter yielded higher removal rates for all the functional groups considered. Indeed, the mean LAI values in the natural reserve, which reflect tree ecophysiological conditions [52], were higher for all three functional groups. This discrepancy between the overall MC of Rome, which is classified as one of the 'greenest' cities in Europe [25], and the Castelporziano Presidential Estate is likely due to the harsh conditions to which trees in the urban environment are exposed, including urban heat island that reduce photosynthesis and transpiration, limited nutrient availability in the soil, overbuilding and other biotic and abiotic stress factors [53–56]. Bearing this in mind, foresight management of GI aimed at preserving a suitable environment for vegetation would improve its functional status, and consequently enhance its removal capacity. Further studies are also needed to shed more light on PM deposition processes related to PM with other aerodynamic diameters, such as the particularly harmful fine PM ($PM_{2.5}$) and ultrafine $PM_1$. Nowak et al. [17] reported that urban trees remove substantially less $PM_{2.5}$ than $PM_{10}$. Moreover, in their study on an urban park, Silli et al. [47] reported that vegetation contributed to a greater extent to the abatement of $PM_{10}$ (12.84%) than to that of a finer PM fraction ($PM_{2.5}$, 2.56%), confirming reports by Yin et al. [57] for urban parks in China. Modeling ecological processes do, however, have certain limitations. In particular, the simulation of $PM_{10}$ deposition on vegetation entails approximating $PM_{10}$ deposition velocity to the plant canopy ($V_d$), which depends on other, more complex parameters besides LAI, such as wind speed, relative humidity and air temperature [58]. Although a more accurate modeling of this parameter is beyond the scope of our work, a finer local-scale analysis, as previously also highlighted by Escobedo and Nowak [42], is warranted to better quantify air pollution removal, and consequently to assess its monetary value, in order to provide management alternatives to policy-makers. It should also be borne in mind that the use of a moderate resolution sensor such as MODIS, particularly in a Mediterranean environment, which is characterized by a high degree of landscape heterogeneity, may affect LAI values regarding the contribution made by different vegetation types to the signal received by the sensor, or may underestimate LAI values in small patches of vegetation [59]. The monetary assessment thus depends on the accuracy of the biophysical modeling, but has certain intrinsic limitations. Indeed, the monetary evaluation does not, but should, take into account the cost of the management and maintenance of the GI, particularly in Mediterranean areas, where particularly stressful summer conditions require additional management practices to improve ES provisions by urban green, such as irrigation, phytosanitary treatments and pruning [54].

## 5. Conclusions

The removal of $PM_{10}$ by urban and peri-urban forests, which is performed above all by deciduous species in the summer months, but also on a more constant basis by the evergreen community, would contribute considerably to the improvement of air quality in the MC of Rome, an area characterized by a high population density, relatively high air pollution levels and marked land use changes related to agricultural and industrial practices. Indeed, around 22% of the 535,200 hectares that make up the MC of Rome are covered by a forest ecosystem whose $PM_{10}$ removal corresponded to an overall monetary value of 161.78 million Euros for the year 2015. Since citizens can benefit from multiple ES provided by natural ecosystems, urban development strategies should increasingly be aimed at enhancing the natural and artificial GI network so as to comply with ES provision and human health recommendations. "The European Green City Index", a research project sponsored by Siemens (2009) [60], showed that out of the 30 leading European cities in 30 different countries, the City of Rome was placed 17th for air quality and 23rd for environmental governance, which refers to the strategies adopted to improve and monitor environmental performance. Social policies must develop and plan funding aimed at promoting infrastructures with a low environmental impact (with low emission levels of greenhouse gases and other pollutants) and nature-based solutions by taking into account ES values.

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