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Mapping and Assessment of PM_{10} and O_3 Removal by Woody Vegetation at Urban and Regional Level

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Abstract: This study is the follow up of the URBAN-MAES pilot implemented in the framework of the EnRoute project. The study aims at mapping and assessing the process of particulate matter (PM_{10}) and tropospheric ozone (O_3) removal by various forest and shrub ecosystems. Different policy levels and environmental contexts were considered, namely the Metropolitan city of Rome and, at a wider level, the Latium region. The approach involves characterization of the main land cover and ecosystems using Sentinel-2 images, enabling a detailed assessment of Ecosystem Service (ES), and monetary valuation based on externality values. The results showed spatial variations in the pattern of PM_{10} and O_3 removal inside the Municipality and in the more rural Latium hinterland, reflecting the spatial dynamics of the two pollutants. Evergreen species displayed higher PM_{10} removal efficiency, whereas deciduous species showed higher O_3 absorption in both rural and urban areas. The overall pollution removal accounted for 5123 and 19,074 Mg of PM_{10} and O_3, respectively, with a relative monetary benefit of 161 and 149 Million Euro for PM_{10} and O_3, respectively. Our results provide spatially explicit evidence that may assist policymakers in land-oriented decisions towards improving Green Infrastructure and maximizing ES provision at different governance levels.

Keywords: Ecosystem Services; Sentinel-2; MAES; Geographic Information Systems; Green Infrastructure; pollutant removal; human health; well-being

1. Introduction

Mapping and assessment of Ecosystem Services (ES) is very important for supporting stakeholders with management practices focused on increasing the provision of goods and services ecosystems can supply [1,2], harmonizing the processes of urban and regional sprawl, and land use change [3–5] with maximum service delivery. The spatial representation of ES is a pillar of the "EU biodiversity strategy" that, through Action 5, promotes mapping and assessment of the state of ecosystems and their services in Member States, in order to achieve an accounting and reporting system at the EU and national levels by 2020 [6]. The mapping and assessment of ES (MAES) require an interdisciplinary effort [7], and owing to the spatial complexity and variability of ES, Remote Sensing and Geographical Information Systems (GIS) have been applied as useful tools in collecting basic data and in carrying out spatially explicit analyses [8–10].

Remote Sensing provides observations suitable for building data sets at varying spatial and temporal scales [11,12]. Therefore, it can be used for landscape representation and analysis of vegetation [13,14], which are the first steps toward ES mapping and assessment [15]. Lately, more sophisticated satellite sensors have become available, providing opportunities for enhancing the accuracy of mapping and assessment of ecosystem goods and services [16]. Among such satellites, Sentinel-2 missions (developed in the frame of the Copernicus Programme) provide images of high spatial (10 m), spectral (13 bands), and temporal (5 days with both Sentinel-2A and Sentinel-2B) resolutions, allowing for more accurate characterization of vegetation. Moreover, Sentinel-2 features three red edge bands ranging from near infrared to far infrared, enabling more precise characterization of vegetation, such as in physiological terms (i.e., water and chlorophyll content) [17].

Detailed land cover and vegetation structure maps can be generated using the information collected from Sentinel-2 [18], thus providing a more detailed base information layer such as ecosystems characterization. Indeed vegetation structure is at the base of assessment of many regulating ES such as carbon storage, climate regulation, and pollutants removal [19]. Among these ES, air quality improvement—through the removal of particulate matter (PM) and tropospheric ozone (O_3) by vegetation—has received increasing attention owing to its effects on public health [20,21], particularly in metropolitan areas, where population density is high and growing steadily [22]. Previous studies have highlighted that the removal of PM_{10} and O_3 are affected by the structural characteristics and functional diversity of forest types, respectively, which are effective indicators of the performance of Green Infrastructure (GI) such as urban and peri-urban forests [23–25]. GI was introduced as an approach towards nature-based solutions addressed at improving human well-being with a noteworthy monetary value [26] because human exposure to PM_{10} and O_3 in cities exceed the legislative limits. Of the 28 EU member states, 21 were found to have PM_{10} concentrations above the EU daily limit, and in general, 50% of the urban population in the 28 member states are exposed to PM_{10} concentrations exceeding the WHO limit [27]. Lately, O_3 concentration has been showing a more complex trend, with peaks decreasing as a consequence of the precursors' decline, but with background concentrations increasing [28]. In addition to differences in national levels, the emission rate of precursors and climatic conditions vary across European countries, resulting in large regional differences in PM_{10} and O_3 concentrations [29]. In this context, Italy faces a critical issue related to the combination of high emission and long-lasting periods of atmospheric stability during the winter, resulting in high PM_{10} concentration [30], and the high temperature and irradiance that typically occur in Mediterranean climate conditions during the summer, leading to high O_3 concentrations [31,32].

The removal of PM_{10} and O_3 by vegetation is highly context dependent, owing to the high spatial and temporal variability of functional and structural parameters for estimating ES and also dependent on the pollutant concentration [9,24].

Thus far, most studies on PM_{10} and O_3 removal across Europe have been focused on urban areas [8,33–35], or at least in metropolitan context [9,24], but few studies have been conducted at the regional level [36,37]. Moreover, to effectively enable the usage of information in maps by stakeholders, the scale at which ES are assessed should follow the administrative levels (municipality, metropolitan cities, regional level). This will aid in coping with political requests [38], fulfilling important indications relative to critical factors and potential areas of intervention for implementing nature-based solutions to air quality mitigation.

In this field of interest, following the MAES Urban Pilot [6,39], the two year project 'Enhancing Resilience Of Urban Ecosystems through Green Infrastructure' (EnRoute) has been developed. The project aims at integrating the MAES approach into local policies, connecting different governance levels (both horizontally and vertically), and contributing to the deployment of Green Infrastructure in cities and urban contexts.

The present study was developed in the framework of the EnRoute project, aimed at analyzing the spatial patterns of PM_{10} and O_3 removal by woody vegetation in the Latium region relative to the municipality of Rome. The land cover, as well as PM_{10} and O_3 concentration patterns in this area, vary widely, characterizing ES supply at different levels of governance.

2. Methods

2.1. Study Area: The Latium Region and the Municipality of Rome

This study was carried out in the Latium Region, focusing on the Municipality of Rome. Latium is located on the western side of Central Italy (41°53′35′′N 12°28′58′′E) and covers 17,232 km^2, with roughly six million inhabitants. The region presents different climatic regimes depending on the distance from the Tyrrhenian Sea, and has complex morphology and lithology. Climatic conditions vary from temperate with large amounts of precipitation in the inner mountains areas to typically Mediterranean along the coastal areas [40]. Owing to the environmental heterogeneity and biogeographic complexity, the Latium Region features highly diverse tree species that are often located within national and regional parks [41], as well as numerous natural reserves [42].

The ecosystem types vary widely owing to the high heterogeneity of the territory: the Simbruini mountains in the northeast are characterized by the widespread presence of deciduous oak woods (*Quercus cerris* L., *Quercus pubescens* Willd.) and beech woods (*Fagus sylvatica* L.), whereas the Lepini mountains, in the south side feature typical evergreen broadleaves (*Quercus ilex* L. and *Quercus suber* L.). Furthermore, the Alban hills in the southeast predominantly include chestnut woods (*Castanea sativa* L.), and volcanic mountains (the Tolfa and Sabatini mountains) in the northwest are characterized by mixed broadleaved forests.

The Municipality of Rome covers 1286 km^2, and has a population of more than 2,700,000, being the most populated municipality in Italy. The geomorphology of Rome is characterized by different landforms, including lowlands, volcanic plateaus, clayey and sandy coasts, and the Tiber alluvial plain [43].

Despite the strong urban sprawl, the Municipality of Rome hosts large urban forests inside historical villas and green areas characterized by considerable biological diversity, including evergreen forests and deciduous woodlands [41]. Moreover, the Municipality of Rome, includes the Castelporziano Presidential Estate at approximately 20 km from the urban center. This estate is a natural reserve of around 60 km^2, characterized by high biodiversity and relatively mature forests [44]. Its climate is strictly Mediterranean and hosts typical Mediterranean ecosystems (maquis shrubland and holm oak forests), as well as several deciduous oak communities and pine plantations.

2.2. Ecosystem Mapping

To estimate the amount of ES provided by the forest and shrub ecosystems in the study area, ecosystem mapping was conducted through a supervised classification of Sentinel-2 images recorded from 25 June to 3 September 2016. The study area is represented by seven different Sentinel-2 images that were mosaicked and georeferenced into the WGS84 UTM32N reference system. The images had a spatial resolution of 10 m, and were selected on the basis of a cloud cover less than 5%. Pixels affected by cloud cover were replaced by corresponding pixels of cloud free images acquired during the summer of 2016. The following elaborations were conducted with the open source software QGIS through the Semi-Automatic Classification Plugin [45]. Radiometric calibration and Dark Object Subtraction (DOS1) were performed, which enabled the supervised classification using a maximum likelihood algorithm. From the CORINE Land Cover legend, 12 classes were readapted to the land cover of the study area, comprising artificial surfaces, agricultural areas, water bodies, and nine Physiognomic-Structural Vegetation Classes (PSVCs). Thus, considering the wide territory analyzed, our classification has a high thematic and spatial accuracy for the purpose of the work. Once classified, all the images were verified against Google Maps in order to visually identify any mismatches in the classification. If present, any classification error (i.e., omission or commission) was manually corrected.

2.3. Air Pollutant Concentration

Annual mean PM_{10} and O_3 concentration data for the year 2010 with a spatial resolution of 4 km were produced by the AMS-MINNI modelling system [46]. Starting from institutional emission inventories and simulated meteorological data, the model simulates atmospheric chemical and physical processes, providing air pollutant concentrations. One of the model components, FARM (Flexible Air Quality Regional Model) [47], simulates transport and chemical modifications of pollutants in the atmosphere by means of SAPRC-99 gas-phase chemical mechanism [48], AERO3 [49,50] for aerosol dynamics, ISORROPIA [51] for aerosol inorganic chemistry, and SORGAM [52] for secondary organic aerosol formation. The meteorological model RAMS (Regional Atmospheric Modelling System) was used to reconstruct the meteorological fields [53]. The model was validated for both meteorological parameters and pollutant concentration. For further details on the emission inventories, domains, input data, and model set-up, see [24,54]. In the context of the present paper the pollutant concentrations simulated with the AMS-MINNI model provide continuous, well-spaced and representative air concentrations that are not available from measurements.

2.4. Leaf Area Index

The Leaf Area Index (LAI, $m^2 \cdot m^{-2}$), widely used in ecological modelling, is a parameter necessary for the PM_{10} deposition model. In this study, the Moderate resolution imaging Spectroradiometer (MODIS) LAI product MOD12A2H with a spatial resolution of 500 m was used. Eighty-eight images of the Latium Region for the year 2016 were downloaded from the LP DAAC database. The images were acquired at a time interval of eight days, covering a period from 1 January 2016 to 27 December 2016. The NASA software LDOPE (Land Data Operational Products Evaluation) was utilized to pre-elaborate the images, selecting high-quality pixels through quality control (no cloud cover, main algorithm), merging, and reprojecting in the WGS84 UTM32N reference system. The images were further elaborated in QGIS in order to produce the annual mean LAI for the considered year. Given the difference in spatial resolution with the Sentinel-2 classification, missing LAI data for some forested areas were highlighted. To yield a complete LAI map of the study site, the missing data were subsequently produced through a Per Class Mean (PCM) spatial interpolation [55]. Missing data in the MODIS LAI product may be attributable to the classification precision of satellite data; some authors report that unforested areas may increase transmittance and cause underestimation and impossibility to detect signals [56,57]. At coarse spatial resolutions, altered signals from such areas mix with signals of adjacent vegetation, leading to misinterpretation of LAI values. Such misinterpretation may result in classification errors, particularly in areas characterized by heterogeneous land cover [57,58].

2.5. PM_{10} Deposition

The classification of forest and shrub ecosystems, mean annual data on PM_{10} concentration, and average LAI were used to calculate the amount of PM_{10} removed by forest ecosystems, following the methodology of Manes et al. [24] and according to Nowak et al. [59] and Yang et al. [60]:

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

where Q is the amount of PM_{10} removed by each forest ecosystem on 1 m^2 of surface ($\mu g \cdot m^{-2}$), F is the downward flux of pollutant (F, $\mu g \cdot m^{-2} \cdot s^{-1}$), calculated as deposition velocity (Vd, m s^{-1}) multiplied by PM_{10} air concentration (C, $\mu g \cdot m^{-3}$), L is the LAI ($m^2 \cdot m^{-2}$), and T (in seconds) is the vegetative period of the forest ecosystems, that was considered equal to 214 days for deciduous, and 365 days for evergreen species. The deposition velocity was set to a median value of 0.0064 $m \cdot s^{-1}$, based on a mean value of 6 [61] and then adjusted to the actual LAI [62]. The total amount of PM_{10} removed by vegetation was finally calculated by multiplying Q for the surface cover of each forest ecosystem.

2.6. O_3 Absorption

O_3 absorption by the forest ecosystems in the study area was estimated following the methodology applied in Manes et al. [8,24]. The O_3 flux in the leaves is described as:

$$FO_3i = g_s \times [O_3] \times 0.613 \quad (2)$$

where FO_3 represents the instant stomatal O_3 flux in the leaf, expressed in nmol $m^{-2} \cdot s^{-1}$, g_s is the stomatal conductance to water vapor of each forest ecosystem, derived from a review of the literature and from experimental measures performed on the prevalent species [44,63–68], $[O_3]$ is the O_3 concentration in the air (ppb), and 0.613 is the diffusibility ratio between water vapor and O_3. The annual cumulated stomatal fluxes (FO_3cum, nmol$\cdot m^{-2} \cdot year^{-1}$) were calculated by integrating the instant fluxes for the photoperiod, considering eight daily hours and 183 days (from April to October).

As stomatal flux represents, on average, 30% of the total O_3 flux, considering both stomatal and non-stomatal processes, the total O_3 absorption was calculated as follows:

$$FO_3tot = FO_3cum\ /0.3 \quad (3)$$

2.7. Monetary Valuation

The monetary value of the ES of PM_{10} and O_3 removal was calculated using externality values, which can be described as the estimated social cost of pollution (human health, damage to materials and the environment) that is not comprised in the market price of the goods or services that caused the pollution [69], usually expressed in cost per Mg of pollutant. As O_3 is a secondary pollutant, its value was assumed to be equal to the value estimated for its precursor, NO_x. These values, estimated for the Italian environmental context [70], are equal to 31,356 and 7798 Euro per Mg of PM_{10} and O_3, respectively, and are calculated on the basis of the conservative value of a life year (VOLY).

3. Results

3.1. Ecosystem Mapping

Figure 1 shows the ecosystems of the study area, obtained through the classification of Sentinel-2 images. The classification accuracy was estimated to be 82%. The 12 classified land cover types comprise nine PSVCs. The main land cover type in the municipality of Rome is agricultural land, covering about 60% of the municipality surface, followed by artificial surfaces (around 30%), characterizing the widespread urban matrix of the city. The Castelporziano Presidential Estate, a natural reserve where a large part of the vegetation of the city is present, is clearly noticeable in the southern part of the municipality. Deciduous oak prevailing woods represent the main vegetation type in the municipality, covering 11,747 ha (Table 1) mainly in the Estate, followed by Mediterranean pine woods, covering 2411 ha. Within the municipality, the third most abundant PSVC is Mediterranean maquis, covering 511 ha, followed by forests predominated by evergreen oak prevailing woods, mountain coniferous woods, chestnut woods and mixed broadleaved woods. Similarly, outside the municipality boundaries (Latium region), agricultural areas represent the principal land use (60%), and the most abundant PSVC is represented by deciduous oak woods (210,419 ha). Artificial surfaces, mainly aggregated in minor urban centers and industrial areas, account for approximately 6% of the Latium region. In addition, chestnut woods (80,075 ha) are also abundant, mainly in the Alban hills area, along with mixed broadleaved woods and beech woods (71,428 and 58,257 ha, respectively), particularly in the Simbruini mountains. Evergreen oak woods and mountain coniferous woods also represent a significant part of the Latium land cover, extending 51,542 and 12,300 ha, respectively. Mediterranean maquis and Mediterranean pine cover 5829 and 3592 ha, respectively, whereas hygrophilous species are the least prominent, covering approximately 9 ha.

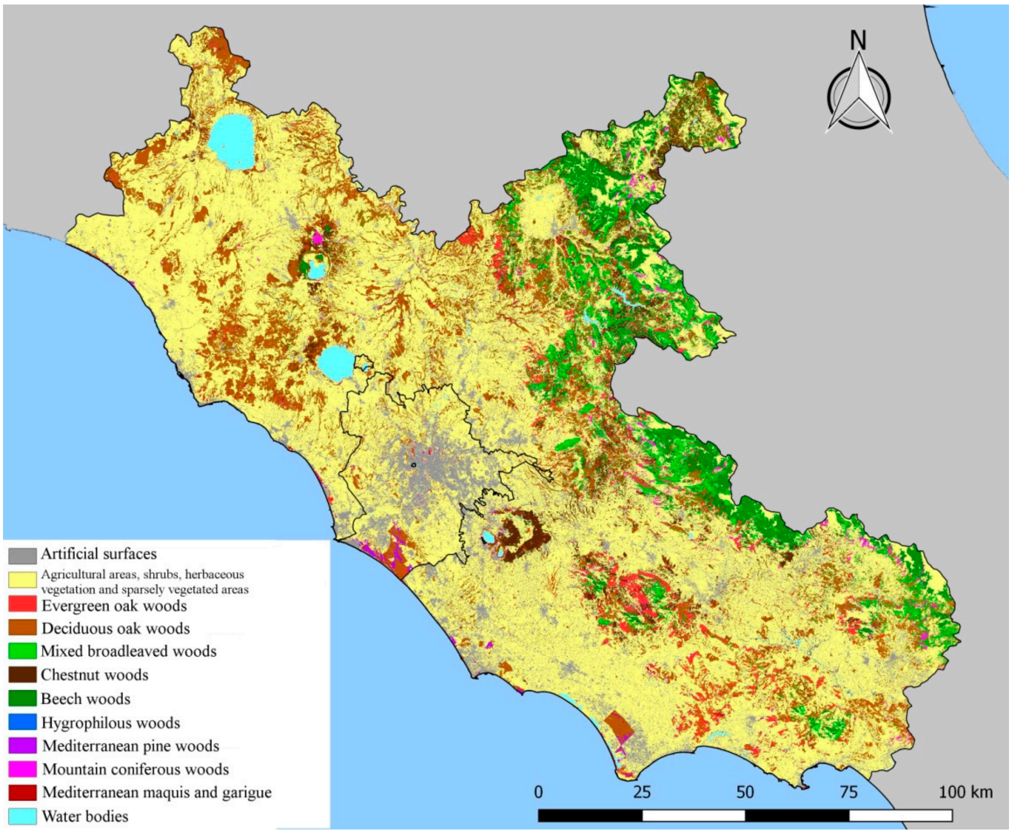

Figure 1. Land cover classification of the of the Latium region using Sentinel-2 images. The area inside the outline represents the Municipality of Rome.

Table 1. Surface cover (ha) of nine Phisiognomic-Structural Vegetation Classes (PSVC)s in the Municipality of Rome and in the Latium region.

PSVCs	Municipality of Rome	Latium Region
Evergreen oak woods	407.2	51,542.4
Deciduous oak woods	11,746.9	210,418.7
Mixed Broadleaved woods	10.6	71,427.9
Chestnut woods	143.0	80,075.1
Beech woods	0.0	58,256.9
Hygrophilous woods	0.0	1665.9
Mediterranean pine woods	2410.8	3591.8
Mountain Coniferous woods	207.9	12,300.0
Mediterranean maquis	511.2	5829.2
Total	15,437.6	495,107.9

3.2. Leaf Area Index

The distribution of LAI values (Figure 2) presents maximum values up to 5.87 $m^2 \cdot m^{-2}$, with the higher values predominantly corresponding to forested areas. In particular, higher LAI values are observable for evergreen species. Inside the municipality of Rome, higher values are noticeable inside the Castelporziano Presidential Estate (from about 3–5 $m^2 \cdot m^{-2}$), whereas other areas show values around 0.5–2.5 $m^2 \cdot m^{-2}$. Outside the municipality boundaries, higher values are evident for most natural forested areas of the Latium Region, such as the Simbruini regional park in the north and the Alban hills in the southeast, as well as rural areas around lakes in the northwest, such as the Tolfa beech woods.

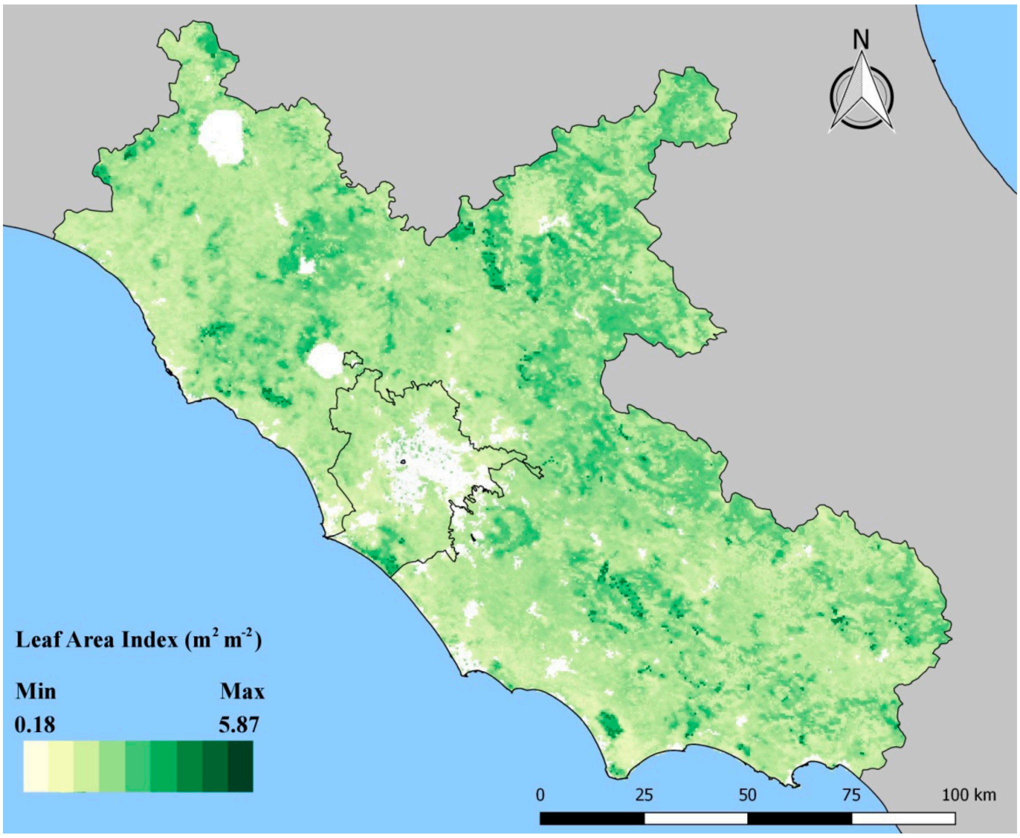

Figure 2. Leaf Area Index ($m^2 \cdot m^{-2}$) map derived from MODIS LAI product (2016).

Among mean LAI values grouped according to PSVCs (Table 2), chestnut woods in the Latium region show the highest value (2.46 ± 0.69 $m^2 \cdot m^{-2}$), and mountain coniferous woods in the municipality have the lowest values (1.67 ± 0.38 $m^2 \cdot m^{-2}$). In the municipality, two types of deciduous woods (mixed broadleaved woods, and deciduous oak woods) present lower LAI values compared to evergreen woods types and Mediterranean maquis. In the Latium region, deciduous and evergreen oak present similar LAI values in relation to those of the Municipality (2.25 ± 0.74 $m^2 \cdot m^{-2}$ and 2.09 ± 0.86 $m^2 \cdot m^{-2}$ for the former, 2.44 ± 0.82 $m^2 \cdot m^{-2}$ and 2.43 ± 0.93 $m^2 \cdot m^{-2}$ for the latter), whereas Mediterranean maquis and garigue, as well as pine woods and mountain coniferous woods present lower values compared to those of the municipality. Beech and hygrophilous woods are not present in the Municipality.

Table 2. Leaf Area Index (LAI) annual mean value ($m^2 \cdot m^{-2}$) for the 9 PSVCs inside the Municipality of Rome and in the Latium region.

PSVCs	Municipality of Rome	Latium Region
Evergreen oak woods	2.43 ± 0.93	2.44 ± 0.82
Deciduous oak woods	2.09 ± 0.86	2.25 ± 0.74
Mixed broadleaved woods	2.01 ± 0.23	2.36 ± 0.65
Chestnut woods	1.84 ± 0.43	2.46 ± 0.69
Beech woods		2.30 ± 0.58
Hygrophilous woods		1.70 ± 0.55
Mediterranean pine woods	2.41 ± 0.80	1.99 ± 0.83
Mountain coniferous woods	1.67 ± 0.38	2.09 ± 0.66
Mediterranean maquis and garigue	2.43 ± 0.84	2.03 ± 0.74

3.3. PM_{10} Deposition

As shown in the PM_{10} removal map of the study area (Figure 3), the distribution of PM_{10} removal ($g \cdot m^{-2}$) presents an ascending trend from the north towards the south of the region and the city center, following the PM_{10} concentration (see Supplementary Materials, 1-A). Beech woods in the northeastern part of the Latium region display values around 0.3–0.8 $g \cdot m^{-2}$, and deciduous, chestnut, and deciduous oak woods show 1–1.5 $g \cdot m^{-2}$. Removal rates continue to rise for evergreen oak woods towards the south (approximately 2.5–5 $g \cdot m^{-2}$), while values as high as 4–5 $g \cdot m^{-2}$ can be observed in the city center. Elevated removal rates are observable in the Castelporziano Presidential Estate (around 5–7 $g \cdot m^{-2}$), with peak removal rates around 12 $g \cdot m^{-2}$. The total annual PM_{10} removal calculated for different PSVCs (Table 3) shows that, despite total removal (Mg) increasing generally with surface extension (Table 1), removal per hectare is higher for evergreen species in the Municipality of Rome: Mediterranean pine woods (0.0382 $Mg \cdot ha^{-1}$), Mediterranean maquis (0.0378 $Mg \cdot ha^{-1}$), evergreen oak woods (0.363 $Mg \cdot ha^{-1}$), and mountain coniferous woods (0.0221 $Mg \cdot ha^{-1}$). In contrast, lower values are observable for mixed broadleaved woods (0.0075 $Mg \cdot ha^{-1}$), chestnut woods (0.0090 $Mg \cdot ha^{-1}$), and deciduous oak woods (0.0138 $Mg \cdot ha^{-1}$). The Latium region also shows a similar pattern, although with slightly lower values: evergreen species have elevated removal rates, with the highest values for evergreen oak woods (0.0206 $Mg \cdot ha^{-1}$), followed by Mediterranean pine woods (0.0178 $Mg \cdot ha^{-1}$), Mediterranean maquis (0.0170 $Mg \cdot ha^{-1}$), and mountain coniferous woods (0.0134 $Mg \cdot ha^{-1}$). Hygrophilous woods display the lowest rate (0.0053 $Mg \cdot ha^{-1}$), followed by beech woods (0.0060 $Mg \cdot ha^{-1}$), and other deciduous species. The monetary valuation of the ES evidences a value of 9.2 million Euro for the Municipality of Rome and of 151 million Euro for the surrounding Latium region, with an overall value of 161 million Euro.

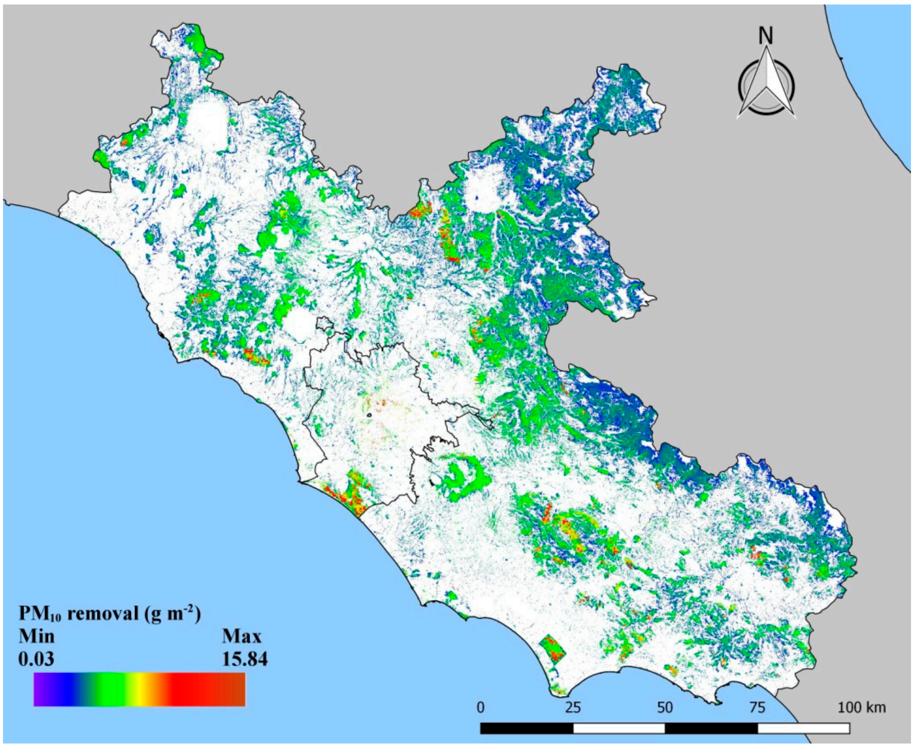

Figure 3. Map of annual PM_{10} removal ($g \cdot m^{-2}$).

Table 3. PM_{10} removed in the Municipality of Rome and in the Latium region, expressed as total removal (Mg) and removal per hectare ($Mg \cdot ha^{-1}$), and its monetary value ($€ \cdot 10^6$).

PSVCs (Municipality of Rome)	Mg	$Mg \cdot ha^{-1}$	Value ($€ \cdot 10^6$)
Evergreen oak woods	14.80	0.0363	0.464
Deciduous oak woods	161.73	0.0138	5.071
Mixed broadleaved woods	0.08	0.0075	0.003
Chestnut woods	1.29	0.0090	0.040
Beech woods	n.a	n.a.	n.a
Hygrophilous woods	n.a.	n.a.	n.a.
Mediterranean pine woods	92.00	0.0382	2.885
Mountain coniferous woods	4.59	0.0221	0.144
Mediterranean maquis	19.34	0.0378	0.606
Total	293.83	0.0190	9.213
PSVCs (Latium Region)	**Mg**	**$Mg \cdot ha^{-1}$**	**Value ($€ \cdot 10^6$)**
Evergreen oak woods	1060.53	0.0206	33.254
Deciduous oak woods	1822.75	0.0087	57.154
Mixed broadleaved woods	523.68	0.0073	16.421
Chestnut woods	734.60	0.0092	23.034
Beech woods	351.18	0.0060	11.011
Hygrophilous woods	8.83	0.0053	0.277
Mediterranean pine woods	64.02	0.0178	2.007
Mountain coniferous woods	164.80	0.0134	5.167
Mediterranean maquis	99.31	0.0170	3.114
Total	4829.69	0.0098	151.440

3.4. O_3 Absorption

The map of O_3 removal (Figure 4) shows variations in absorption values from 0.7 to 11.2 $g \cdot m^{-2}$. Low values are present inside the municipality of Rome and in the coastal sector, although O_3 mean concentrations are higher in this area (see Supplementary Materials, 1-B). The southeastern part of the region also displays low removal values, where evergreen oak forests are present. The highest rates are noticeable in the northeastern areas of the Latium region, characterized by the presence of vast deciduous forest stands as beech woods and chestnut woods. Regarding the annual O_3 removal values (Table 4), it is noticeable that deciduous species present the highest removal rate. Inside the Municipality of Rome, chestnut woods remove 0.0601 Mg per hectare, while deciduous oak woods remove 0.0337 Mg per hectare. Elevated values are present for Mediterranean maquis, (0.0365 $Mg \cdot ha^{-1}$), while the lowest values were estimated for mountain coniferous woods (0.0190 $Mg \cdot ha^{-1}$), and Mediterranean pine woods (0.0197 $Mg \cdot ha^{-1}$). Similarly, in the surrounding Latium region, elevated values are present for deciduous species. In particular the highest value is shown by hygrophilous woods, with 0.0977 Mg removed per hectare, followed by chestnut woods (0.05992 $Mg \cdot ha^{-1}$), and beech woods (0.0570 $Mg \cdot ha^{-1}$). Mediterranean maquis also presents elevated removal rates (0.0375 $Mg \cdot ha^{-1}$), along with deciduous oak woods (0.0336 Mg ha^{-1}). Lower rates are evident for Mediterranean pine woods (0.0201 $Mg \cdot ha^{-1}$), and evergreen oak woods (0.0240 $Mg \cdot ha^{-1}$). The monetary valuation showed an overall value of around 149 million Euro (3.783 million Euro estimated for the Municipality of Rome and 145.024 million Euro outside the Municipality).

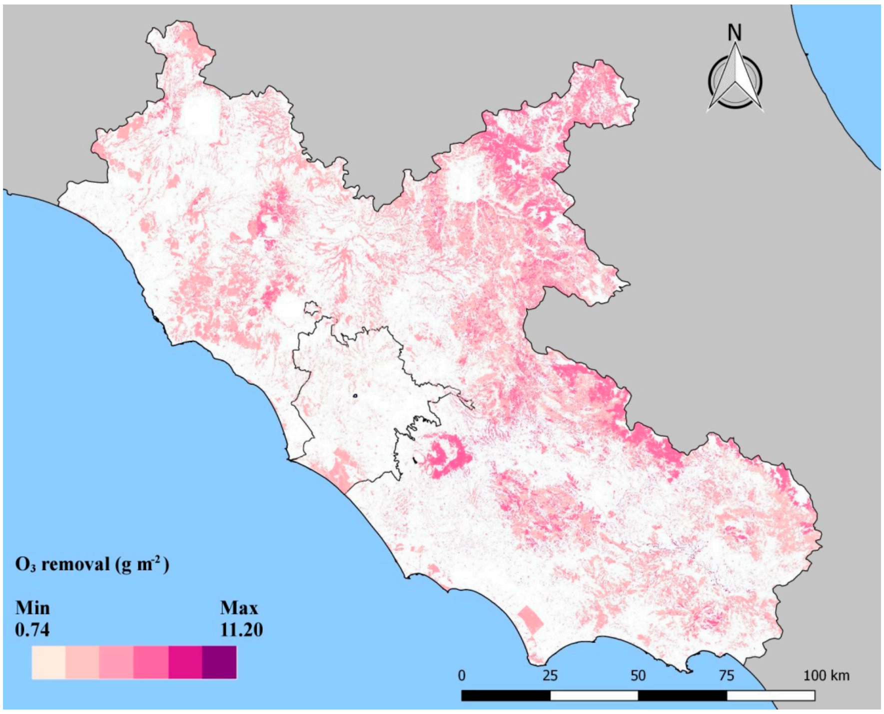

Figure 4. Map of annual O_3 removal (g·m^{-2}).

Table 4. O_3 removed in the Municipality of Rome and in the Latium region, expressed as total removal (Mg) and removal per hectare (Mg·ha^{-1}), and its relative monetary value (€·10^6).

PSVCs (Municipality of Rome)	Mg	Mg·ha^{-1}	Value (€·10^6)
Evergreen oak woods	9.86	0.0242	0.077
Deciduous oak woods	396.32	0.0337	3.091
Mixed broadleaved woods	0.29	0.0274	0.002
Chestnut woods	8.6	0.0601	0.067
Beech woods	n.a.	n.a.	n.a.
Hygrophilous woods	n.a.	n.a.	n.a.
Mediterranean pine woods	47.43	0.0197	0.370
Mountain coniferous woods	3.96	0.0190	0.031
Mediterranean maquis	18.68	0.0365	0.146
Total	485.14	0.0314	3.783
PSVCs (Latium region)	**Mg**	**Mg·ha^{-1}**	**Value (€·10^6)**
Evergreen oak woods	1238.25	0.0240	9.656
Deciduous oak woods	7068.85	0.0336	55.123
Mixed broadleaved woods	1675.61	0.0235	13.066
Chestnut woods	4737.02	0.0592	36.939
Beech woods	3322.55	0.0570	25.909
Hygrophilous woods	162.81	0.0977	1.270
Mediterranean pine woods	72.30	0.0201	0.564
Mixed coniferous woods	101.46	0.0082	0.791
Mediterranean maquis	218.77	0.0375	1.706
Total	18,589.34	0.0375	145.024

4. Discussion

The study represents the first step toward the operationalization of the URBAN-MAES-framework at the city scale. In order to contribute to enhancing the quality of the framework, as requested by the EnRoute project, we extend the spatial characterization of pollutant removal to understudied areas as well as rural and secondary urban levels (i.e., districts) in the Latium region [71]. Even if administrative boundaries are not often satisfactory units for ES mapping because they do not coincide with ES dynamics [10], we promote this approach to enhance the science-policy exchange and to promote better the potential of nature-based solutions in the field of air quality improvement. We focused on the capacity of vegetation to ameliorate air quality through PM_{10} and O_3 removal at the municipality (City of Rome) and regional (Latium) levels. A technical contribution to improve the quality of the framework is provided through the Sentinel-2 classification (spatial resolution at 10 m) of the Latium region land cover. It is worth noticing that Sentinel-2 images allow for frequent update of the map, and the identification of specific land cover classes; nevertheless, European data such as Corine Land Cover could be used for the analysis of previous years when Sentinel-2 images were not available. The technical approach we used represents an update of the current vegetation type classification at such spatial scales, and may be a step forward. Furthermore, it may be considered a new standardized method to a more accurately mapping and assessment of ES in areas characterized by high spatial and ecosystem heterogeneity, such as complex urban and peri-urban matrices. Regarding PM_{10} removal, no substantial difference between actual air pollutant removal in the urban center and in the Latium region could be observed, but rather slightly higher values were found inside the municipality. Higher PM_{10} removal values inside the city center are partially attributable to the higher annual mean concentrations of PM_{10} relative to the regional scale. In fact, PM_{10} removal increases towards the city center, in accordance with the PM_{10} concentrations that are particularly critical in such densely populated areas (Supplementary Materials, 1-A), due to the presence of massive emission sources such as high vehicular traffic and domestic heating systems [27]. Annual PM_{10} average concentrations in the Municipality of Rome are close to 40 $\mu g \cdot m^{-3}$ the limit imposed by the European Air Quality Directive (2008/50/EC), and well above the WHO guidelines of 20 $\mu g \cdot m^{-3}$ (WHO, 2006) (see Supplementary Materials, 1-A). In addition to the PM_{10} concentration, it is noteworthy that pollutant removal inside the municipality is positively influenced by the Castelporziano Presidential Estate as well as the widespread urban historical villas that cover more than 1000 ha. These factors contribute to rendering the Municipality of Rome comparable with the Latium Region in terms of regulating ES. This result highlights the key contribution of urban and peri-urban forests to air quality amelioration in the municipality [25,72], where urbanization is diffused and high concentration of pollutants such as PM_{10} exists. Similar to previous studies on other European cities [10] in our study case the hinterland vegetation has more ES potential if compared to the inner urban core, resulting in a higher PM_{10} removal because of the high LAI values [24].

As ecosystems provide ES also in non-local terms, measures at a broader scale (as the Latium region) are required to manage GI in order to tackle air pollution [9]. MODIS images were used for LAI calculation, nevertheless Sentinel-2 images could be considered as a future improvement in the methodology considering the availability of both Sentinel-2A and Sentinel-2B which provide one image every five days.

Regarding the different efficiencies of the PSVCs, evergreen ecosystems perform better at removing PM_{10} than deciduous ecosystems, in accordance with previous studies on the Metropolitan city of Rome [24,25]. This is because of the prolonged vegetative period and the resulting capacity to adsorb particulate matter on the surface of the leaves even in winter months, where PM removal demand is higher [73]. This evidence is valid both at the municipality and regional levels.

It is interesting to highlight that the trend of O_3 removal was reversed owing to the opposite concentration pattern (lower in the city center and higher in rural areas) relative to PM_{10} concentration (see Supplementary Materials, 1-A,B). This difference in O_3 annual mean is attributable to the balance between precursors (i.e., volatile organic compounds) and the prevalent NOx in urban areas that scavenges O_3 [74,75]. Moreover, deciduous species generally perform better than evergreen species in O_3 removal due to their higher stomatal conductance [24,76]. Most of the removal occurred outside municipality boundaries because of the higher abundance of deciduous ecosystems such as oak and beech woods, as well as chestnut and hygrophilous woods.

As current research on GI and ES mapping in relation to human health are quite limited, [9], our study provides spatially explicit information to stakeholders that may be useful for landscape planning strategies at different governance levels. A far sighted management of GI should take into account the different dynamics of the two atmospheric pollutants, which are particularly harmful for human health, inside and outside the city [77], and the different removal patterns of different ecosystems. Many authors pointed out the relation between functional diversity and the enhancement of ES [8,25,78], highlighting the importance to reach an appropriate balance between different ecosystems. Such an achievement would contribute to improving ES provision to further improve nature-based solutions.

Functional diversity could enhance ES provision through the reduction of variations in services at the seasonal scale due to different phenology, diverse inherent functional traits such as stomatal conductance, and leaf morphology, which is mostly related to PM_{10} removal [79]. Moreover, the performance of an ecosystem in pollutant removal also depends on its conservation status. Lately this type of evaluation was carried out at both regional (Latium) and national levels (Italy) [23]. This analysis highlights that for the Latium region, evergreen woods together with mixed broadleaved and beech woods and Mediterranean maquis present a high conservation status, whereas ecosystems more connected with anthropic context such as chestnut, hygrophilous woods, and Mediterranean pine, and mountain coniferous woods have lower levels of conservation. Considering structural and functional characteristics, the assessment of ecosystem conservation status could address restoration practices aimed at maximizing the provision of ES, in accordance with EU Biodiversity Strategy goals and the EnRoute project.

Moreover an important issue should be addressed in GI planning, mostly in urban areas, regards the trade-off between the ecosystem services and disservices, such as the pejorative effect of vegetation on air quality or allergies [80]. Plants emit volatile organic compounds (VOCs), that trigger reactions involved in formation of both PM and O_3 [81]. These compounds are species-specific scaling with many environmental stressors such as water shortage or high temperature [75]. To minimize the disservices, urban development planning should be addressed to select native species well adapted to local environmental conditions [8,82,83]. Moreover, selection criteria used for urban plantations should combine the goal of increasing the provision of the required services with the maintenance of a high biodiversity level [84].

An explicit spatial planning oriented towards the association of different PSVCs, enhancing ecosystem diversity, may provide multiple benefits even in monetary terms. The monetary valuation of ES in this study, accounting for an overall value of about 309 Million Euro [85], can be a useful tool to better orient the interventions of policy makers as the concept of natural capital becomes increasingly important worldwide in understanding the economic implications of human planning of GI. Within this framework, it is important to increase awareness on the role of GI on regulating services that are not properly considered in national economic budgets [86].

5. Conclusions

As air pollution poses an increasing threat to human health, the improvement of air quality is a key target in Europe. In this context, a science-guided management of GI is essential. The mapping and assessment of PM_{10} and O_3 removal in this study provides spatial characterization of ES in a highly populated urban area (Municipality of Rome) and in more understudied and rural areas (Latium region), as requested by Action 5 of the European biodiversity strategy to 2020. The use of detailed data provided a more accurate insight into the role of different ecosystems in PM_{10} and O_3 removal, and the different intrinsic spatial patterns of these ecosystems inside and outside the urban area. The potential of GI in countering air pollution, evaluated also in monetary terms, is highlighted, underlining the contribution of nature-based solutions in meeting air quality standards and increasing resilience in urban areas. This study provides a baseline on the characterization of ES in this territory and represents the first step towards a more in-depth focus on ecosystem conditions and processes.

This study will serve as a reference for active processes aimed at involving local stakeholders for urban and peri-urban forest management and standardizing ES mapping and assessment at the European scale through cross-scale comparison.

Supplementary Materials: The following are available online at www.mdpi.com/2072-4292/9/8/791/s1, SM 1-A: Particulate Matter (PM10) annual average concentration map derived from the AMS-MINNI model simulations (2010), SM 1-B: Tropospheric ozone (O3) annual average concentration map derived from the AMS-MINNI model simulations (2010).

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