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Assessment of air pollutants removal by green infrastructure and urban and peri-urban forests management for a greening plan in the Municipality of Ferrara (Po river plain, Italy)

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ABSTRACT

Air pollution is a serious concern for human health and is even more worrying in areas that are known to be "pollution hotspots", such as the Po Plain in northern Italy. The Urban Green Infrastructure (UGI), which includes urban and peri-urban forests, enhances human health and wellbeing delivering a wide range of ecosystem services, including air quality improvement. In this research, we analyzed, in biophysical and monetary terms, the role of the UGI in removing PM_{10} and O_3 from the atmosphere in the Municipality of Ferrara using established removal models. We used a multiscale approach that includes geospatial data, field sampling and laboratory analysis. Then, using a local green areas database, we located public areas that could potentially undergo forestation actions without requiring any land conversion and evaluated the benefit in terms of ESs provision that these actions may exert. We found that, in 2019, the UGI in the Municipality of Ferrara removed about 19.8 Mg of PM_{10} and 8.6 Mg of O_3, for a monetary benefit of € 2.12 million € and $147*10^3$ respectively. We then identified about 121 ha within the urban core of the Municipality that could potentially be forested. Such an action would increase the PM_{10} and O_3 removal by about 49% and 18%, respectively. Our findings comply with the EU Biodiversity strategy for 2030, which calls for the development of an ambitious greening plan for cities with more than 20,000 inhabitants.

1. Introduction

Air pollution is a global challenge, and is currently considered to be the most important risk to human health (EEA, 2020). According to the European Environment Agency (EEA, 2020), PM pollution caused about 52,300 premature deaths in 2018 in Italy, by enhancing the incidence of lung diseases, cancer, and stroke; in the same period, the O_3 caused about 3,000 premature deaths. In addition, long-term exposure to air pollutants affects the respiratory and cardiovascular systems, leading to an increase in the COVID-19 death rate (Zhu et al., 2020; Accarino et al., 2021). In Europe, sectors such as transport, commercial, household, energy production, industry, and agriculture highly contribute to the emission of pollutants into the atmosphere (EEA, 2019); the formation and accumulation of air pollutants also depend on local factors such as climatic conditions (Ferrero et al., 2011).

In this framework, alongside emissions reduction policies (Lafortezza et al., 2018), the EU has encouraged the use of *Nature-based Solutions* (NBS) to effectively contrast air pollution. NBS enhance the environmental quality, as well as the growth and conservation of the Natural Capital and may help to shift towards a greener economy (Capotorti et al., 2020). In particular, the Urban Green Infrastructure (UGI), which encompasses urban and peri-urban forests and other elements such as street trees, provides a wide range of Ecosystem Services (ESs) (EC, 2013). For example, the UGI plays a pivotal role in improving the air quality of urban ecosystems by removing different air pollutants (Manes et al., 2012a and 2016; Baumgardner et al., 2012) and by mitigating the Urban Heat Island effect (Marando et al., 2019).

Increasing the provision of ESs is a major challenge in compact cities

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(Hansen et al., 2019; Grêt-Regamey et al., 2020). Dense urban environments demand ES of urban trees, yet existing green spaces to plant new trees are scarce and the conversion of non-green areas is expensive and complex. Nonetheless, while urban green spaces are limited, increasing their quality is a pressing need (Haaland and Van der Bosch, 2015). Raising the presence and coverage of trees are widely recognized as valuable measures to increase the multifunctionality of UGI (Reid et al., 2017; Jim et al., 2018; Belmeziti et al., 2018; Manes et al., 2012a). This is also evident in the EU biodiversity strategy for 2030 (EC, 2020), which remarks the need for protecting and restoring well-functioning ecosystems and requires cities with at least 20,000 citizens to develop an ambitious urban greening plan by the end of 2021.

The biophysical assessment of ESs has increasingly been used to support decision-makers in defining management policies (Burkhard & Maes, 2017); the economic evaluation of ESs may also represent a valuable tool for highlighting the relevance of natural ecosystems to society (Capriolo et al., 2020). Notwithstanding, mapping Regulating ES is complex (Wei et al., 2017), as it requires a deep understanding of those structures and processes that underpin the considered ES (Crossman et al., 2013). As a consequence, the NBSs are not systematically included in sustainable planning strategies (Woodruff and BenDor, 2016; Sebastiani et al., 2021a).

This research aimed firstly to assess the role of the urban and peri-urban forests of the Municipality of Ferrara (northern Italy) in removing the PM_{10} and O_3 from the atmosphere. The Municipality of Ferrara was selected as an ideal case study, since it is representative of the river Po plain, an area that suffers from high air pollution levels due both to direct emissions and its geomorphological features. Secondly, by accessing a local green areas database (data provided by the Municipality of Ferrara), we identified areas that could potentially undergo forestation actions without requiring land conversion, and evaluate a scenario in which the UGI of the Municipality is enhanced. A monetary evaluation of air quality improvement service is also performed, to demonstrate the relevant socio-economic benefits of planting trees in urban areas and provide arguments to support future investments in enhancing the UGI. We adopted a multi-scale approach that relies on field sampling, laboratory analysis, geospatial data such as remote sensing data and the Corine Land Cover (CLC) inventory, and modeling techniques. Our findings are also oriented to support stakeholders toward the development of an urban greening plan for the Municipality, according to the EU biodiversity strategy for 2030.

2. Materials and methods

2.1. Study area

The Municipality of Ferrara (44°50′07.07″N; 11°37′11.51″E, Fig. 1) is located in the middle of the Po plain, Northern Italy, at approximately 9–13 m a.s.l. The Po plain is one of the major air pollution hotspots in Europe (Bigi and Ghermandi, 2014; Diémoz et al., 2019); indeed, several factors concur to raise the air pollution in that area. First, the agricultural sector, which has a strong influence on the local air quality, is highly developed (Lonati and Riva, 2021). Then, winters are characterized by a very low wind speed, and temperature inversion is frequent (Caserini et al., 2017); therefore, due to the reduced ventilation, the accumulation of primary pollutants and the formation of secondary

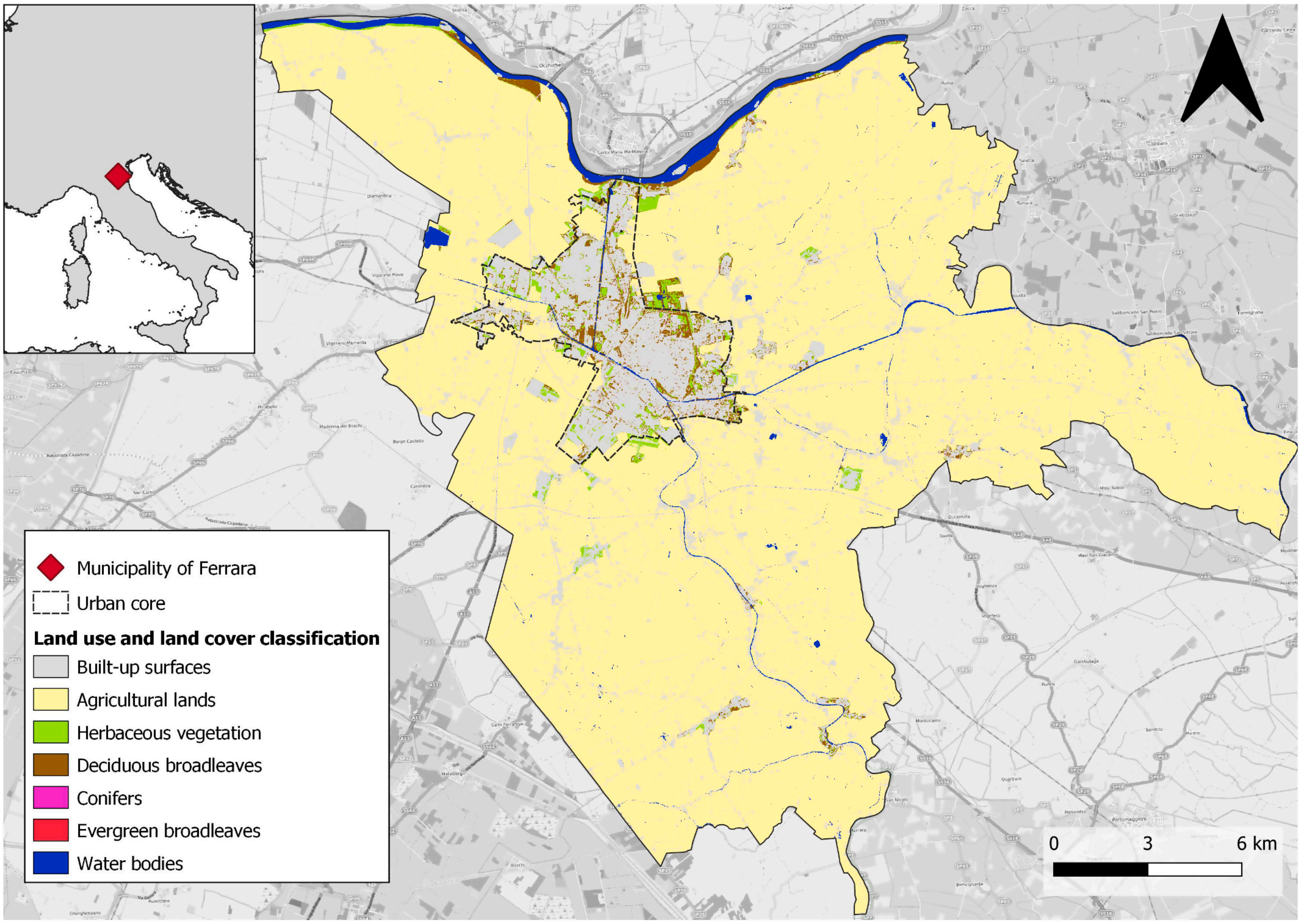

Fig. 1. Land use/land cover classification of the Municipality of Ferrara.

pollutants are favored (Carbone et al., 2010; Ferrero et al., 2011).

Ferrara covers an area of 405.16 km^2, of which about 4.74 km^2 is included within the ancient city walls, and has 132,899 inhabitants who reside mostly in the compact urban core (ISTAT, 2020), with a population density of about 328 inhabitants km^{-2}. The annual precipitation is about 814 mm yr^{-1}; the area can be classified as "Cfa" according to the Köppen-Geiger climate classification (Peel et al., 2007). Following the recently updated ecoregional classification of Italy (Blasi et al., 2018), the Municipality falls in the Po plain province (lagoon subsection, code 1B1a), which embeds the northern part of the Italian Adriatic coast.

The potential vegetation in the inner part of the Po plain is essentially made by Querco-carpinetum forests with *Quercus robur*, *Carpinus betulus* and *Acer campestre* (Blasi et al., 2010). The natural vegetation has almost entirely been removed to maximize the space for agricultural activities. A major role is played by the riparian vegetation along the Po riverside, which includes *Populus alba*, *Fraxinus angustifolia,* and *Quercus robur* (Blasi et al., 2010).

According to the National Census of urban green areas (ISTAT, 2019), the public green areas of Ferrara account for 8.2 km^2. The ancient city walls extend for 9 km and are surrounded by an urban green fringe with appreciable levels of biodiversity (Pellizzari et al., 2015). In addition, other small public and private parks and gardens are present on the municipal territory (Fig. 1).

The urban flora of Ferrara encompasses 589 vascular species, more than 100 of which are aliens (Pellizzari et al., 2015). Following the public trees' census (data provided by the Municipality of Ferrara, 2018), *Celtis austalis, Tilia* × *europea, Platanus* × *acerifolia, Populus nigra, Acer negundo,* and *Robinia pseudoacacia* are the most abundant species. Evergreen broadleaves and conifers are poorly represented in the Municipality, being respectively *Magnolia grandiflora, Quercus ilex,* and *Picea abies*, *Cedrus atlantica, Thuja sp.*

2.2. Land use/land cover classification

We identified 7 land use/land cover classes for the study area: built-up surfaces, agricultural areas, herbaceous vegetation, water bodies, and 3 different functional groups of vegetation, that is, deciduous broadleaves, evergreen broadleaves, and conifers (Manes et al., 2012a). Ecosystem mapping was conducted using different data sources.

The built-up surfaces were detected based on the National Land Consumption map produced by ISPRA (Munafò et al., 2019), which is made through photointerpretation and semiautomatic classification of satellite images and is delivered as a 10 m resolution raster. The agricultural areas were extracted from the Corine Land Cover 2018 dataset, which has a minimum mapping unit of 25 ha; specifically, we extracted class 2, which refers to the agricultural areas, including pastures, arable lands, and permanent crops. The herbaceous and woody vegetation was mapped performing a supervised classification of two Sentinel-2 images, acquired during summer 2019. We adopted the maximum-likelihood algorithm to assign each pixel to its land use and land cover class; the classification was performed utilizing the SCP plug-in implemented in QGIS (Congedo, 2020). We used the Sentinel-2 Level-2A products, which provide Bottom Of Atmosphere (BOA) reflectance and are systematically generated over Europe and freely delivered by the European Space Agency. At last, conflicts between different data sources were solved using ground truth data and field observations carried out by the experts of the University of Ferrara. The accuracy of the land use/land cover classification was evaluated using field observations and ground-truth data.

2.3. Seasonal leaf area Index retrieval

Direct measurements of the Leaf Area Index (LAI) are time-consuming and labor-intensive, and can only be conducted within small areas like isolated trees, single fields, or parks (Xie et al., 2019). In this research, the seasonal LAI was computed processing the Level-2A Sentinel-2 data (two cloud-free images for each season) within the biophysical processor module of the Sentinel Application Platform (SNAP) software. The biophysical processor uses 8 different spectral bands and other information such as solar zenith, viewing zenith, and relative azimuth angles (Kganyago et al., 2020); it is based on a pre-trained artificial neural net. The output consists of a 10 m resolution raster covering the study area, which we used to estimate the LAI of the different functional groups of vegetation. Due to the unprecedented spatial resolution, the LAI product derived from the described methodology will be increasingly used for a wide range of applications. Preliminary studies have shown that Sentinel-2 derived LAI has a good accuracy when compared to field data (Brown et al., 2021); however, this product still needs comprehensive validation over different regions and for different periods of the year (Hu et al., 2020).

2.4. Pollution data

The Monthly PM_{10} and O_3 concentrations were retrieved from the Emilia-Romagna ARPA (Regional Environmental Protection Agency) monitoring system. Pollution data was taken from the monthly report of Air quality, freely available on the ARPAE website (https://www.arpae.it/it). We used monthly data from the monitoring stations named Barco Nuova (urban-industrial), Villa Fulvia (urban background) and Corso Isonzo (urban traffic) to estimate the seasonal average concentrations. To avoid any bias caused by the 2020 pandemic, we decided to use 2019 pollution data. Then, we assumed that the seasonal PM_{10} and O_3 concentrations were homogeneous for the study area.

2.5. Air pollutants removal by vegetation

To estimate the PM_{10} removal, we adopted the methodology proposed by Manes et al. (2016), Fusaro et al. (2017), and Nowak et al. (1994). The following equation was used:

$$Q = F^{*}L^{*}T \tag{1}$$

where Q is the quantity (kg) of the pollutant removed by the vegetation; F $\left(\frac{\mu g}{m^{2}{*}s}\right)$ is the flux of the pollutant, which is a function of the PM_{10} concentration and the deposition velocity (Vd) of particles on the leaves; L is the LAI; T is the vegetative period of each functional group of vegetation, which was set to 365 days for evergreen species and 214 days (from early spring to mid-autumn) for deciduous species.

The deposition velocities of the three functional groups (deciduous broadleaves, evergreen broadleaves, and conifers) were experimentally measured (Eq.2). The 11 most representative tree species for the Municipality of Ferrara were selected. Twelve samples of branch leaves were taken for each tree species (three samples × four trees), close to the monitoring stations for PM_{10}, to obtain reliable measures of PM air concentrations before and during sampling events. The PM_{10} deposition velocity for the sampled leaves was estimated using the vacuum filtration method, following the methodology proposed by Sgrigna et al. (2015). The total leaf area of broadleaf samples was measured through ImageJ (Schneider et al., 2012) upon direct leaf scan and considered as double-sided. The leaf area of conifers was estimated by assuming that needles have a cylindrical shape. The surface of a single needle was estimated by multiplying needle length by needle girth. The latter was measured making the cross-sectional slice in the middle part of the needle. The individual surfaces of 20 needles were measured to obtain a mean value and then multiplied by the number of needles present in each branch sampling. Samplings were carried out after at least 10 dry days (i.e. days occurred after the last precipitation event). The deposition velocity was computed considering the mean PM_{10} adsorbed by leaf samplings of the three functional types and the PM_{10} air concentration in the dry days before samplings, according to the following equations:

$$V_d = \frac{F_h}{PM_{air}*0.000036} \tag{2}$$

where Vd is the deposition velocity (cm s^{-1}), F_h is the mean hour flux (g $m^{-2}h^{-1}$) and PM_{air} is the mean PM_{10} air concentration during the d dry days before sampling (μg m^{-3}).

$$F_h = \frac{PM_{leaf}}{100*24*d} \tag{3}$$

where PM_{leaf} is the amount of PM_{10} measured on the leaf sampling (μg cm^{-2}) after d dry days before sampling.

The O_3 removal was computed following the methodology proposed by Manes et al., (2012a). First, we calculated the stomatal O_3 flux referred to 1 m^2 of forested soil surface:

$$FO_{3(i,p)} = gs_{(i)}*[O_3]_{(i,p)}*0.613 \tag{4}$$

where FO_3 is the stomatal ozone flux, gs is the mean annual stomatal conductance $\left(\frac{molH_2O}{m^2*s}\right)$, retrieved from field and laboratory data, $[O_3]$ is the mean seasonal Ozone concentration, *0.613* is the ratio of diffusivity between Ozone and water vapor, i and p refer to the day of the year and location respectively. $FO_{3(i,p)}$ was then integrated over time for the entire study area, to estimate the cumulative amount of O_3 which is seasonally removed by the vegetation:

$$FO_{3cum(p)} = \left(\sum_{i=1}^{n} FO_{3(i,p)}*Ph*\frac{1}{R}\right) \tag{5}$$

where n is the number of cumulative days (which is equal to 183), Ph is the photoperiod expressed in s, and R is the $\frac{stomatal}{total}$ flux ratio. A number of 183 cumulative days was chosen since Ozone is mostly concerning during the hot periods of the years, which in our case occur from April to October (Fusaro et al., 2017). All the modelling elaborations were carried out using the GRASSGIS software.

2.6. Monetary evaluation

The monetary evaluation was conducted following the methodology proposed by Fusaro et al. (2017). We used the externality values, that is, an estimated social cost of air pollution that is not included in the market price, including the detrimental effect on human health, environment, and man-made materials (EEA, 2020). In our case, the externality is expressed in euros per Mg of pollutants removed by the vegetation. The externality values are equal to € 107,384 and € 17,110 per PM_{10} and O_3 respectively. Those are calculated based on the conservative value of a life year (VOLY), integrating different scientific and economic disciplines (EEA, 2020).

2.7. Identification of spaces for the urban forestation and enhancement of ESs

The area for the urban forestation was extracted from the public green space's database of the Municipality, which is spatially explicit and reports the current intended use of the area (e.g., parks, sports facilities, street trees, etc.). Potential conversion from agricultural land or brownfields to forested areas was not considered in the analysis. In selecting suitable spaces, we excluded all the areas smaller than 1 ha, which are in most cases connected to residential buildings and schools as well as street greening; we also excluded private areas and sports facilities such as football fields and racecourses. Spaces devoted to religious purposes were ignored, as those areas provide a wide range of cultural and recreational ESs (Langemeyer et al., 2015). Lastly, we did not consider areas close to high historical-values sites such as the ancient city walls, which may need specific conservation and management measures and are subject to landscape and historical constraints. After this first screening, we mapped the portion of the suitable area which is not currently covered by woody vegetation, assuming that it can be subject to forestation actions.

We then hypothesized to reforest the above-mentioned areas with equally distributed evergreen broadleaves, deciduous broadleaves, and conifers; precisely, young plants of autochthonous species should be preferentially chosen (Loures et al., 2007). Soil and climate conditions in the study area can support species from the three functional groups of vegetation. In fact, the soil of Ferrara municipality is quite homogeneous (Emilia-Romagna Region, 2010) and there are no relevant restrictions for urban forests. Thus, no significant spatial differences in vegetation growth and performances are expected.

We focused on the urban core of the Municipality of Ferrara since such area is densely populated and highly demanding for ESs; therefore the enhancement of the NBSs would provide benefits to the majority of the people living in the city. Eventually, we estimated the benefit in the PM_{10} and O_3 removal, in biophysical and monetary terms, that this forestation action would provide to the Municipality.

3. Results

3.1. Ecosystem mapping

Fig. 1 shows the land cover classification of the study area. Agricultural areas cover the majority of the Municipality (almost 82%). Built-up surfaces cover slightly more than 13% of the Municipality and are mostly located in the urban core. The combination of the functional groups of vegetation, covers about 697 ha, which equates to 1.7% of the total surface of the Municipality. The three functional groups of vegetation are not equally present: 97% (677 ha) of the total vegetation belongs to the deciduous broadleaves; about 3% (21 ha) belongs to the conifers group; the presence of evergreen broadleaves is very scarce (about 1 ha). About 43% (about 297 ha) of the woody vegetation can be found within the urban core. Water bodies cover almost 3% of the Municipality. The accuracy of the classification was estimated to be slightly higher than 80%.

3.2. Seasonal leaf area Index

Fig. 2 shows the seasonal LAI maps for the urban core of the Municipality; due to the scarcity of evergreen species, winter data is not shown. Quantitative values are reported in Table 1. Deciduous broadleaves show moderate values in spring and autumn (2.1 and 1.7 respectively) and peak during summer (3.0). The seasonal LAI of conifers spans from a minimum of 1.4 in winter to a maximum of 2.4 during summer, whereas evergreen broadleaves show small LAI variations amongst the different seasons, with the lowest value (1.5) in winter, and the highest (2.3) in summer.

3.3. Pollutants levels and PM_{10} deposition velocity

PM_{10} levels (year 2019) are highest in winter (50.4 μg m^{-3}), followed by spring (36.9 μg m^{-3}), summer (30.3 μg m^{-3}), and autumn (29.1 μg m^{-3}). O_3 levels (year 2019) are higher during summer (53.8 μg m^{-3}), followed by autumn (48.7 μg m^{-3}), spring (41.3 μg m^{-3}) and winter (19.3 μg m^{-3}).

Table 2 summarizes the V*d* and the related standard deviation for each functional group. The V*d* of deciduous broadleaves is equal to 0.545 cm s^{-1} (st.err. ± 0.0024); V*d* for conifers is 1.458 cm s^{-1} (±0.109); V*d* for evergreen broadleaves is 0.79 cm s^{-1} (±0.152).

3.4. Air pollutants removal by vegetation and monetary evaluation

Figs. 3 and 4 show the seasonal PM_{10} and O_3 removal by the urban and peri-urban forest in the Municipality; quantitative results are reported in Tables 3 and 4. Due to the scarcity of evergreen species, winter

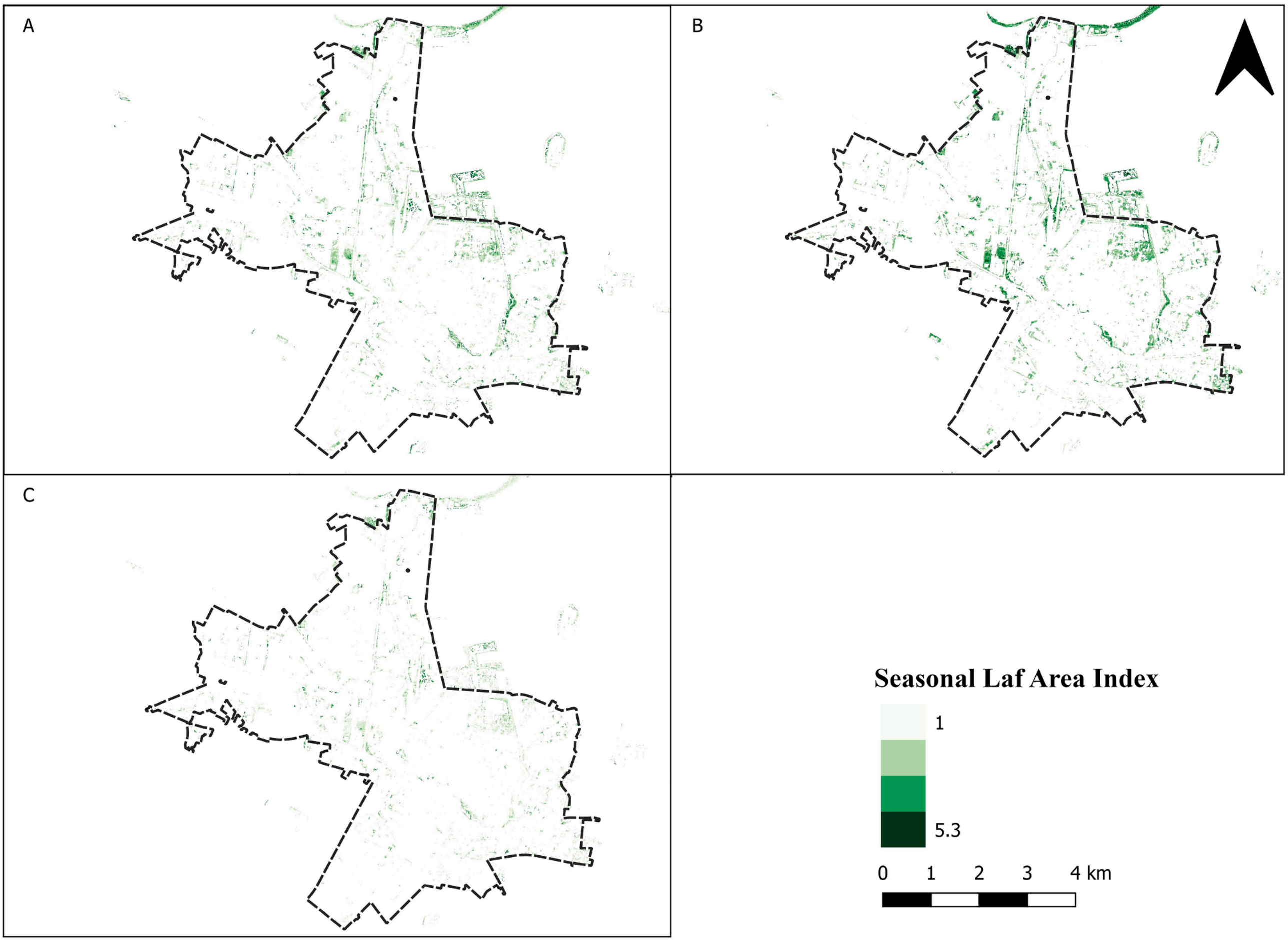

Fig. 2. Seasonal LAI for spring (A), summer (B) and autumn (C). Due to the scarcity of evergreen species, the winter map is not shown.

Table 1
Mean seasonal Leaf Area Index derived from Sentinel-2 data.

Vegetation group	**Season**			
	Winter	**Spring**	**Summer**	**Autumn**
Deciduous broadleaves	0	2.1	3.0	1.7
Evergreen broadleaves	1.5	1.8	2.3	1.7
Conifers	1.4	2.1	2.4	2.0

Table 2
Mean PM_{10} deposition velocity experimentally measured and the corresponding mean sampled leaf area (±st.err.)

Vegetation group	PM_{10} Deposition Velocity (cm s^{-1})	Sampled Leaf Area (cm^2)
Deciduous broadleaves	0.54 ± 0.02	5806.3 ± 766.3
Evergreen broadleaves	0.79 ± 0.15	1536.3 ± 149.6
Conifers	1.46 ± 0.11	1816.0 ± 248.0

maps are not shown.

As for the PM_{10}, a total of 19.78 Mg have been removed by the vegetation in the Municipality for the considered year. Conifers have by far the highest annual removal rate (145.4 kg ha^{-1} y^{-1}), and their total contribution to the PM_{10} removal is about 7% of the total. The major contribution in absolute terms is provided by the deciduous broadleaves, which remove about 18.35 Mg of PM_{10}, that is, 93 % of the total. Deciduous broadleaves show the highest removal rate in summer, which is equal to 21.0 kg ha^{-1} y^{-1}. The role of the evergreen broadleaves is negligible, as those are very scarce for the study area. The monetary benefit derived from the PM_{10} removal amounts to about € 2.12 million for the considered year (2019).

Concerning the O_3 removal, a total of 8.6 Mg have been removed by the vegetation in the Municipality for the considered year (Table 3). The highest removal efficiency has been observed for deciduous broadleaves (17.52 kg ha^{-1} y^{-1}), followed by evergreen broadleaves (13.03 kg ha^{-1} y^{-1}) and conifers (9.20 kg ha^{-1} y^{-1}). The monetary benefit derived from the O_3 removal amounts to about € 147.1 *10^3 euros for the considered year (2019).

3.5. *Identification of spaces for the urban forestation and enhancement of ESs*

The area respecting the established criteria for being subject to forestation actions covers about 151.5 ha within the Municipality; about 80.2% (121.5 ha) of this area is not currently covered by woody vegetation (Fig. 5). In the scenario in which the 121.5 ha are forested using equally distributed evergreen broadleaves, deciduous broadleaves, and conifers, the woody vegetation of the urban core would increase by about 40.9%, passing from about 297 ha to about 418.5 ha. The yearly PM_{10} removal would increase by 9.69 Mg, that is, about 49% of the current removal. Interestingly, the winter removal would increase by 579%, which is by far the highest increase among all the seasons. As for the O_3 removal, it would increase by 1.61 Mg, that is, 18.70% of the current removal, with no relevant differences for the different seasons.

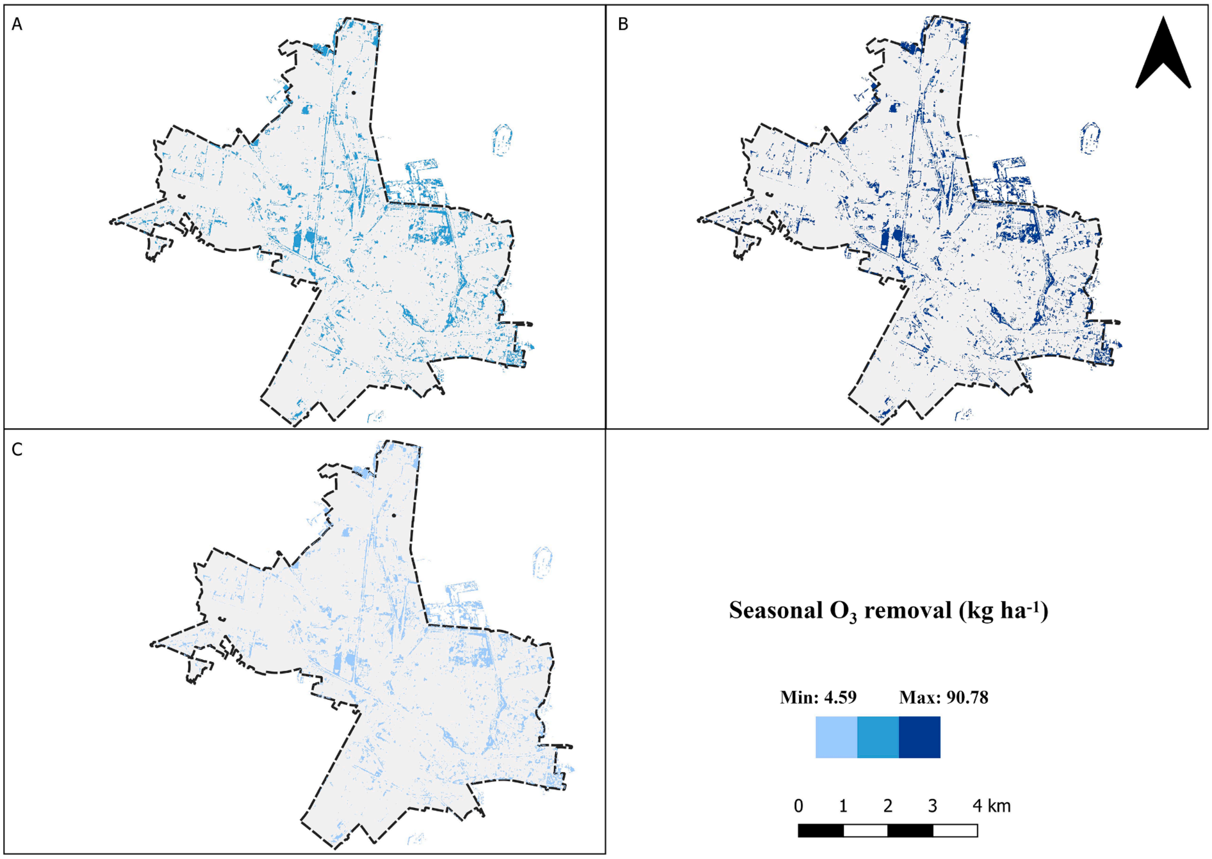

Fig. 3. PM_{10} removal for spring (A), summer (B) and autumn (C). Due to the scarcity of evergreen species, the winter map is not shown.

Concerning the monetary benefit, its yearly increment would be equal to € 1.04 million and € 27.54*10^3 for PM_{10} and O_3 removal respectively.

4. Discussion

Unlike other bigger cities like Rome (Manes et al., 1997; Fusaro et al., 2015), Milan (Sanesi et al., 2017), and Naples (Appolloni et al., 2018; Sebastiani et al., 2021b), the Municipality of Ferrara cannot rely on large urban parks or historical villas. This may be attributable to the highly agricultural vocation of the territory, and to the tendency in maximizing the available space for agriculture. Within the urban core, the compactness of the urban settlement reduces the available space for forestation. The current UGI in the Municipality lacks functional diversity since more than 97% of the total woody vegetation belongs to the deciduous broadleaves. According to different research (Cadotte et al., 2011; Manes et al., 2012a, 2016), the functional diversity of vegetation stabilizes the provision of regulating ESs due to differences in phenology, inherent functional traits such as stomatal conductance, and leaf morphology. Therefore, we argue that any forestation action within the Municipality should keep this in mind.

Overall, for all functional groups, most of the PM_{10} removal came during summer. This is owing to the fact that in summer the vegetation has completed the vegetative growth; thus if conditions such as water or heat stress don't take place, a high LAI, which is related to the PM_{10} removal by vegetation (Manes et al., 2016) can be observed. The superior PM_{10} removal efficiency of conifers is due to the higher deposition velocity. The deposition velocity is influenced by the leaf's surface structure as well as by the chemical characteristics of cuticle wax (Chen et al., 2015), and several authors found out that V*d* is higher for coniferous species rather than broadleaved species (Freer-Smith et al., 2005; Popek et al., 2013; Petroff et al., 2008).

As for the O_3, the majority of the removal for all the functional groups of vegetation occurs during summer; this result was expected, as the O_3 concentrations are notoriously favored during the hot season. The highest removal efficiency is observed for deciduous broadleaves, mostly due to their higher stomatal conductance compared to the other functional groups (Manes et al., 2012b).

It is important to remark that an ESs assessment alone is not sufficient to properly select tree species for forestation actions; indeed, trees may also provide the so-called ecosystem disservices, thus generating health problems for the people living nearby (Velasco-Jiménez et al., 2020). For example, trees may contribute to the formation of tropospheric O_3 by emitting biogenic volatile organic compounds (BVOCs), which can act as an O_3 precursor (Calfapietra et al., 2013; Fitzky et al., 2019). Furthermore, it is necessary to assess both ESs supply and demand to choose areas where the ESs should be primarily enhanced (Sebastiani et al., 2021a).

New forestation plans should pursue multiple objectives besides the environmental quality of the area, including social, economic, and cultural development (Guarini et al., 2020). In this regard, the Municipality of Ferrara is promoting participatory approaches for the reforestation of specific areas, with the involvement of citizens, local stakeholders, technicians, and other experts to identify the demand for different uses of new forested areas. Such an approach aims to design urban green areas that intercept the needs of the local population while increasing its awareness and knowledge of the ecosystem services provided by UGI.

Suitable areas for forestation (Fig. 5) could be extremely valuable, also to enhance the functional diversity of vegetation. The scenario would mostly benefit from the winter PM_{10} removal, which is the lowest in the current condition, therefore stabilizing the provision of this ES and limiting the extreme fluctuations that have been observed across different seasons. It's worth remarking that, due to the large coverage of agricultural land in the peri-urban territory and to the presence of marginal areas in the urban core, much more potential for reforestation

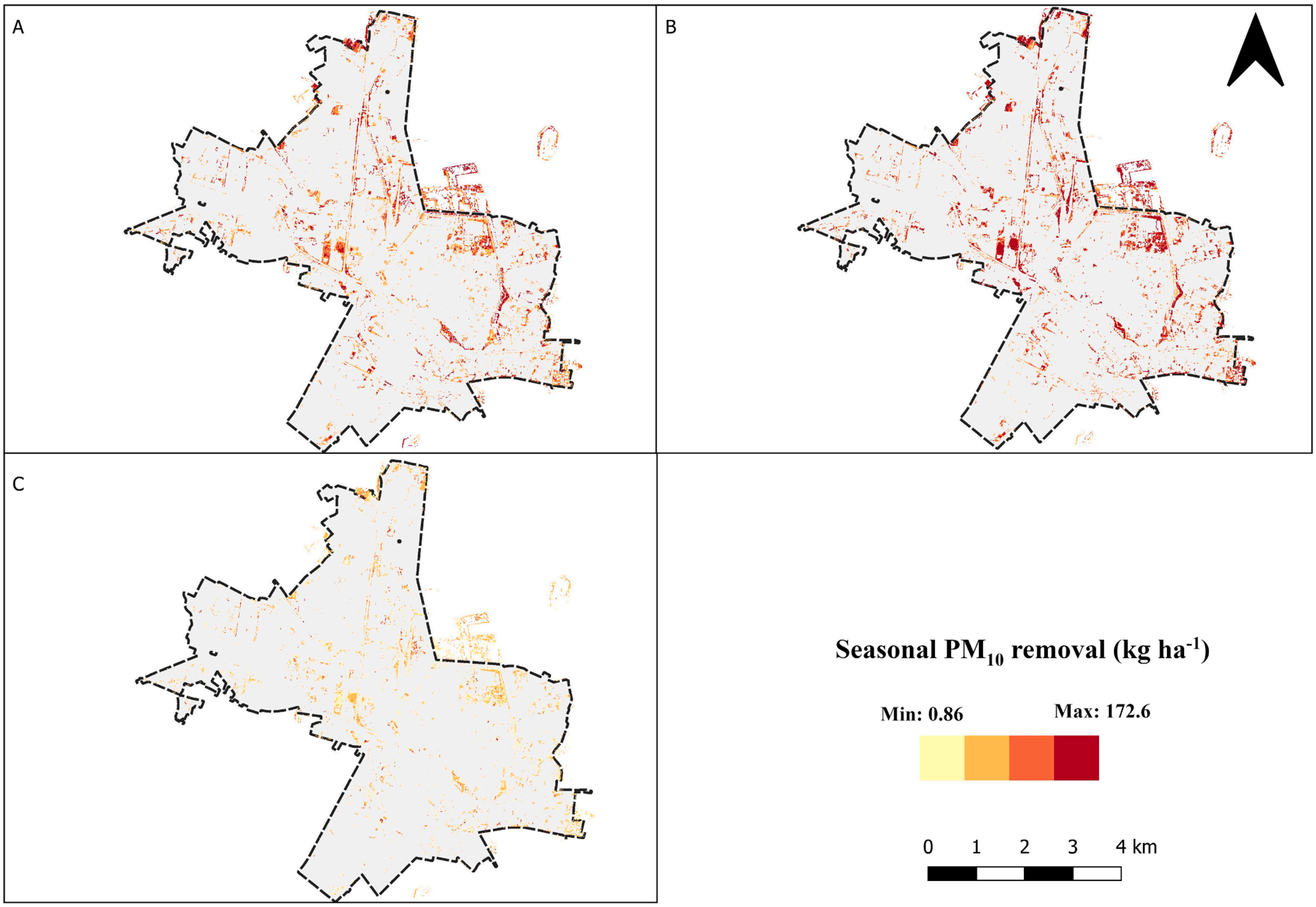

Fig. 4. O_3 removal for spring (A), summer (B) and autumn (C). Due to the scarcity of evergreen species, the winter map is not shown.

Table 3
Seasonal and annual PM_{10} removal and monetary evaluation.

	Winter			*Spring*			*Summer*			*Autumn*			*Annual*		
	Kg	kg/ ha	€ * 10^3	kg	kg/ ha	€ * 10^3	kg	kg/ ha	€ * 10^3	kg	kg/ ha	€ * 10^3	kg	kg/ha	€ * 10^3
Deciduous broadleaves	0.00	0.00	0.00	6700.90	13.81	210.11	10202.30	21.02	319.90	1448.04	2.98	45.40	18351.24	37.81	575.42
Evergreen broadleaves	7.79	12.17	0.38	9.25	14.45	0.29	12.15	18.98	0.38	6.67	10.42	0.21	35.86	56.03	1.12
Conifers	283.22	29.50	0.93	518.14	53.97	16.25	315.18	32.83	9.88	279.72	29.14	8.77	1396.26	145.44	43.78
Total	291.01		1.31	7228.29		226.65	10529.63		330.17	1734.43		54.38	19783.36		620.33

Table 4
Seasonal and annual O_3 removal and monetary evaluation.

	Spring			Summer			Autumn			Annual		
	kg	kg/ha	€*10^3	kg	kg/ha	€*10^3	kg	kg/ha	€*10^3	kg	kg/ha	€*10^3
Deciduous broadleaves	3283.43	6.76	25.61	4798.88	9.89	37.423	423.57	0.87	3.30	8505.88	17.52	66.33
Evergreen broadleaves	3.09	4.83	0.024	4.52	7.06	0.035	0.73	1.14	0.005	8.34	13.03	0.06
Conifers	34.28	3.55	0.267	50.11	5.19	0.39	4.44	0.46	0.034	88.83	9.20	0.69
Total	3320.80		25.89	4853.51		37.84	428.74		3.34	8603.05		67.09

measures relies on the possible conversion of croplands and brownfields to green areas. A feasible solution could be represented by Payments for ecosystem services (PES) schemes, which are increasingly used to preserve urban and peri-urban forests and the related ecosystem services in rural settings (Richards and Thompson, 2019). In this sense, the monetary evaluation provided in this study may represent a justification to sustain the economic costs of agricultural land acquisition, the depaving actions, and the PES implementation. The monetary evaluation, which is in line with the ones reported in similar studies (Manes et al., 2012a; 2016; Fusaro et al., 2017), represents a powerful instrument for connecting the ecological and economic perspectives of ESs, and is widely used for defining urban planning and management

Fig. 5. Public green areas selected for forestation actions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strategies (Nikodinoska et al., 2018). Our results may indicate how worth it is to invest in the enhancement of the UGI, and could easily be used by stakeholders and policy-makers as a decision support tool. Nonetheless, it should be borne in mind that other ESs such as carbon storage, flood prevention, and urban heat island mitigation (Velasco et al., 2016; Li et al., 2020; Marando et al., 2019; Maragno et al. 2018) should also be assessed for a comprehensive evaluation. Interestingly, according to the municipal budget of 2020, the Municipality invested about € 4.3 million in the maintenance of public green spaces and enhancement of the natural environment (https://openbilanci.it/), which equates to about 2.7% of the total budget. The expenses for health protection account for about € 805,000, which is lower than the monetary benefits assessed in this study. Moreover, the municipal budget does not include the benefits derived from the UGI, nor monetarily nor under any other perspective.

Our approach presents some general limitations that should be addressed. First, the removal models simplify the processes of PM_{10} and O_3 removal by the vegetation. Factors such as rainfall, wind speed, temperature, and humidity were not addressed. Then, due to the lack of more suitable data, we used average seasonal PM_{10} and O_3 concentration for running the model; this kind of input does not consider the spatial variation of pollutants within the city. As for the O_3 removal, we used the annual average g_s value of the different functional groups of vegetation; this may lead to an overestimation of the removal since conditions such as drought stress significantly reduce g_s (Fusaro et al., 2015). Finally, the air pollutants removal modelled in the reforestation scenario is based on average annual parameters applied in this study (e.g LAI, pollutants concentration, Vd, gs) for the three functional groups.

5. Conclusions

This analysis quantified the benefits in terms of air quality improvement provided by the UGI in the Municipality of Ferrara and proposes a forestation scenario aimed at enhancing the provision of ESs. The scenario involves about 121 ha of existing green areas that are not subject to landscape and historical constraints, and can be used as a starting point for a more refined land planning strategy. The forestation would generate relevant benefits by respectively increasing the PM_{10} and O_3 removal by about 49% and 18%, after reaching tree mature stages.

The plantation of autochthonous tree species represents a feasible and cost-effective solution to tackle air pollution in cities with a dense urban fabric, as well as to enhance its resilience (Jim et al., 2013; Tian et al., 2014; Grote et al., 2016). The results demonstrated that the social costs of air pollution can be significantly reduced by foresting the existing scattered green areas in a city where those are fragmented and scarce, such as the case of the Municipality of Ferrara. Our findings may also help in complying with the EU Biodiversity strategy for 2030, which calls cities to develop an ambitious greening plan by the end of 2021.

The monetary benefit, which is remarkable, represents an argument for enhancing the UGI in forthcoming land planning strategies and could hopefully be included in the Municipality's budget.

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CRediT authorship contribution statement

Alexandra Nicoleta Muresan: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Alessandro Sebastiani:** Conceptualization, Methodology, Data curation, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. **Mattias Gaglio:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Elisa Anna Fano:** Conceptualization, Methodology, Supervision, Resources, Project administration, Funding acquisition, Writing – review & editing. **Fausto Manes:** Conceptualization, Methodology, Supervision, Resources, Project administration, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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