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A "reserve" of regulating services: The importance of a remnant protected forest for human well-being in the Po delta (Italy)

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ABSTRACT

During the last century the landscape of the Po delta (Italy), one of the most important European deltaic areas, was strongly altered by extended land reclamation and land use intensification. Consequently, the loss of the lowland forested area that was once extended along the region's coast took place. The present study aims to evaluate the ecosystem services provided by the Bosco Mesola woodland, a remnant-forested area of 1,058 ha located on an agriculture-dominated landscape, nowadays protected as a National Nature Reserve. Five ecosystem services were selected and evaluated both in biophysical and monetary terms, including provisioning (firewood production for industrial bioenergy and households' heating purposes), regulating (air quality and climate regulation by carbon storage), and cultural services (eco-tourism), using experimental and collected data and modeling. The results underlined that the Reserve provides services for a total 10.4 M€ yr^{-1} and stores carbon for an estimated value of 7.2 M€. Notably, regulating services, such as air quality regulation (i.e. PM_{10} and O_3 removal) accounts for 98.5% of the total annual value. While raising the issue related to the identification and conservation of ESs with no direct market value, whose socio-political and applicative fields have great relevance, this study demonstrates that remnant forests are exceptional providers of ecosystem services that can significantly contribute to reaching multiple sustainable development goals and whose preservation is largely remarked in EU Biodiversity Strategy for 2030. In this regard, the integration of different methods and data sources for ES assessment allow to capture a comprehensive range of ESs that may properly support the decision process.

1. Introduction

Deforestation is one of the most extended and impacting land cover change dynamics worldwide (Waring and Running, 2007). The conversion of forested areas to other land cover types (mainly croplands) and the increasing fragmentation of the remaining forest relicts lead to extraordinary losses in terms of biodiversity and ecosystem services (ESs) (Foley et al., 2007; Mitchell et al., 2014), hampering the pursuit of the UN Sustainable Development Goals (SDG) foreseen by the Agenda 2030. Moreover, the increasing pressures due to human activities and climate change further exacerbate such consequences, causing significant increases in conservation costs (Cunha et al., 2019; Naidoo et al., 2006).

Remnant forests, i.e. untouched forest patches that remained through the landscape change process, play a fundamental role in sustainable development, being strategic natural hotspots in anthropic landscapes. The declaration of protected areas, such as parks, Natura2000 network zones, and Nature Reserves, is the most common safeguard measure adopted to halt the conversion of forested areas and conserve habitats and species. However such measures, which have high associated costs (White et al., 2022), are often insufficient, as these fail to consider drivers acting at wider scales (Gaglio et al., 2020, 2017b), thus hindering the reach of the conservation targets fixed by the EU Biodiversity Strategy to 2030.

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To overcome these constraints, during the last decade, relict natural areas have been embedded within the wider concept of nature-based solutions (Conte et al., 2020; Keesstra et al., 2018). Specifically, they have been increasingly viewed as important landscape components of green infrastructures, defined as "*strategically planned networks of high quality natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services and protect biodiversity in both rural and urban settings*" (European Commission, 2014). In this framework, the valorization of the ESs provided by remnant forests represents an instrument to legitimize conservation efforts and achieve multiple sustainable goals. More generally, nature governance is gradually shifting the view on protected areas from passive conservation instruments to active providers of ESs, adopting a wider social-ecological system perspective (Watson et al., 2014).

Hence, remnant forests are hotspots for both biological conservation and maintenance of ecological functionality on human-dominated landscapes (Valdés et al., 2020). Such areas preserve many of the ESs previously delivered by original landscapes, which went lost after deforestation. In particular, remnant forests contribute to several regulating ESs, e.g. air quality regulation (Sebastiani et al., 2021), soil retention (Li et al., 2020), water quality (Valatin et al., 2022) and global and local climate regulation (Chu et al., 2019; Marando et al., 2019), provisioning, e.g. timber (Kolo et al., 2020), food production (Chamberlain et al., 2020), and cultural services (Sutherland et al., 2016).

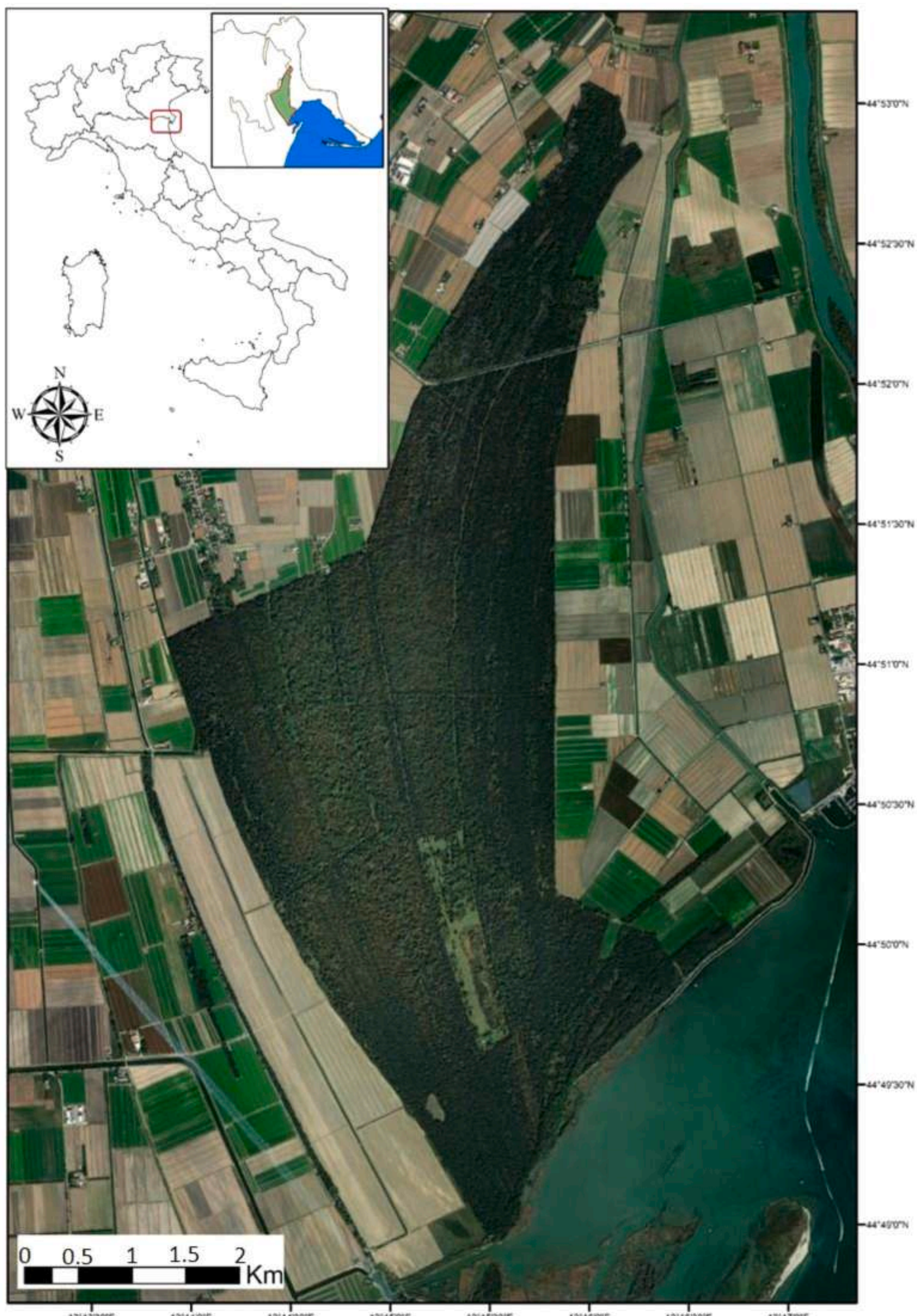

Fig. 1. The Bosco Mesola Reserve and its location within Italian territory. (Source: Esri - World Imagery Map, 2023).

However, the bundles of delivered services vary across different environmental and socioeconomic contexts (Orsi et al., 2020). For instance, soil erosion prevention in stepping slopes, water fluxes regulation, carbon storage and firewood production are among the main functions provided by forested patches in mountainous landscapes (Locatelli et al., 2017), while pollination, pest control, and local climate regulation are usually observed in lowland forests (Kowalska et al., 2021). Air quality regulation strictly depends on leaf structural and ecophysiological traits and air pollution levels (Gaglio et al., 2022), thus underlining the importance of species composition and local environmental conditions on the ES provision. Finally, in the case of cultural services, people's perception is influenced by socioeconomic factors, such as education, income, and population demographic characterization (Lausi et al., 2022). The above mentioned benefits contribute to several SDGs (e.g., SDGs 3, 11 and 13) by supporting human well-being in terms of risk prevention and mitigation, green economy and intangible values. Despite the importance of their environmental and socioeconomic role, ecological functions and services delivered by relict forested areas are still poorly studied.

Some authors investigated the relevance of relict areas for biodiversity (Karp et al., 2019; Magioli et al., 2021), but few studies assessed their provision of ESs, mainly in tropical environments. Particularly, they focused on the evaluation of carbon storage (Aryal et al., 2022; Muluneh and Worku, 2022), pollination (De Marco and Coelho, 2004; Ricketts and Lonsdorf, 2013) and general ES assessment through landscape metrics (Ferraz et al., 2014). Moreover, the majority of these studies concern small multiple patches (Decocq et al., 2016) rather than single large remnant forests. To contribute to filling this knowledge gap, this study aims at quantifying both biophysically and monetarily the main ecosystem services provided by the Bosco Mesola Reserve, a remnant protected forest area located in the river Po delta (Italy), using collected data and well-established models based on experimental quantifications.

2. Materials and methods

2.1. Study area

The Bosco Mesola Reserve (44.85° N, 12.24° E; Fig. 1) is one of the last remnants of a floodplain-forested area that was once extended along the entire region's coast; today, it covers an area of 1058 hectares. The forest has been a National Nature Reserve since 1977, included within the territory of a regional park (the Po delta Park E-R); it is part of the Natura 2000 network as a Special Protected Zone and it is listed by IUCN as a Habitat/Species Management Area. The Reserve is managed by *Reparto Carabinieri per la Biodiversità di Punta Marina* (former National Forestry Corps), which is responsible for environmental conservation and regulates access to the area.

The study area is classified as "Cfa" (humid subtropical climate) according to the Köppen–Geiger climate classification (Peel et al., 2007). The mean annual temperature is 14 °C, with a mean annual precipitation of about 800 mm. The mean annual wind speed is 3.5 m s^{-1} with prevailing directions SW and ENE during the year 2021. The forest lies on a sandy dune system that originated during the 11th to 15th centuries, which is nowadays surrounded by croplands resulting from the extended land reclamation works carried out during the last century (Gaglio et al., 2019, 2017a). The high variety of soil texture and its hydraulic system makes the Bosco Mesola Reserve an important biodiversity hotspot within the agricultural landscape. Its ponds and canals host numerous aquatic macroinvertebrates (Muresan et al., 2020) and plant communities (Gerdol et al., 2018). Furthermore, it is a nesting site for migrating aquatic birds and hosts terrestrial invertebrates, reptiles, and mammals of important conservation value (Contarini, 1994), including a unique subspecies of red deer (*Cervus elaphus italicus*) (Zachos et al., 2014).

Three main ecosystem types constitute the vegetation of the Reserve (Gerdol et al., 1985): a xerophytic *Quercus ilex* community is situated on higher and more recent arid dunes; a mesophilic community with an oak-hornbeam forest mainly covers the more ancient dryer flat dunes; and a hydrophilic ash tree forest community colonizes the dunes slacks that are submerged for most of the year. However, the transition from the xerophytic to the mesophilic habitats often occurs gradually, and *Q. ilex* mainly cohabits with *Carpinus betulus*.

2.2. Ecosystem services evaluation

The Bosco Mesola Reserve provides relevant ESs for human well-being and the achievement of sustainable goals. We identified five ESs as the most important ones for the Reserve, based on its ecological features and environmental management. According to the SEEA EA (System of Environmental Economic Accounting - Ecosystem Accounting) adopted by the EU (La Notte et al., 2017; Edens et al. 2022), these ESs were assessed in both biophysical and monetary terms (Table 1); our assessment followed the CICES classification and is coherent with the ES cascade model (Potschin-Young et al., 2018), according to which ecological processes and functions deliver one or more ESs when meeting human demand. Hence, the approach adopted in this study involved three steps: i) the identification of ecological functions underpinning the ESs delivery, ii) the biophysical quantification through indicators obtained by primary data or modeling, and iii) the monetary evaluation using externalities and market values of the five ESs. The combination of biophysical and monetary accounts within the framework of the SEEA EA provides relevant policy information that can be used beyond a case study level.

2.2.1. Air quality regulation

The vegetation of the Reserve regulates air quality by removing pollutants with high impacts on human health. In particular, the overall PM_{10} and O_3 removal capacity were assessed through two well-established modeling approaches, which rely on land cover data, pollution data, and structural, physiological, and phenological parameters of vegetation. For PM_{10} removal, we used the approach proposed by Nowak et al. (2006), Sebastiani et al. (2021) and Muresan et al. (2022). We computed the removal on a seasonal basis for all of the four seasons; the model is based on the following equation:

$$Q = F \times L \times T \quad (1)$$

where Q is the total amount of pollutant removed by the vegetation expressed in Mg; F (μg/(m^2 s^{-1})) is the flux of the pollutant on leaves, which was computed on a seasonal basis as follows:

$$F_{season} = Vd \times [PM_{10}]_{season} \quad (2)$$

where V*d*, whose computation will be described later in this section, is the deposition velocity of particles on leaves and $[PM_{10}]_{season}$ is the seasonal PM_{10} concentration, retrieved by collecting data from the

Table 1
Evaluated ecosystem services in the Bosco Mesola Reserve. Related ecological functions, indicators and categories (according to CICES classification) are reported.

Ecosystem services category	Ecosystem service	Ecological function	Indicator
Regulation & Maintenance	Air quality regulation	PM removal	kg PM yr^{-1} removed
		Ozone removal	kg O_3 yr^{-1} removed
	Climate regulation	Carbon storage	t C stored
Provisioning	Bioenergy Households' Heating	Firewood production	kWh yr^{-1} kWh yr^{-1}
Cultural	Eco-tourism	Presence and access to natural habitats	Tickets and bike rentals yr^{-1}

closest ARPA (Regional Environmental Protection Agency) monitoring station (44.839749 N, 11.961252 E); *L* is the seasonal Leaf Area Index (LAI); *T* is the period of persistence of leaves, which, being *Q. ilex* and evergreen species, was set equal to the total length of the season, that is, roughly 91.25 days.

The deposition velocity (*Vd*; cm s^{-1}) was experimentally measured as follows:

$$Vd = \frac{F_h}{[PM_{10}] \times 0.000036} \quad (3)$$

where *[PM10]* is the mean PM air concentration in the aforementioned period (μ/m^3), measured by the closest monitoring station. *Fh,* which is the mean hour flux (g m^{-2} h^{-1}), was computed as follow:

$$F_h = \frac{PM_{10leaf}}{100 \times 24 \times d} \quad (4)$$

where $PM_{10\ leaf}$ is the amount of PM measured on the leaf (μg cm^{-2}) after *d* dry days before sampling using vacuum filtration method.

$PM_{10\ leaf}$ was experimentally measured with a sampling campaign carried out on 14th September 2021, thirteen days after the last rain event (2.8 mm, 31th August) as registered by the local weather station. To investigate possible differences among zones and potential edge

Fig. 2. Sampling points (four transects and two central points) for the measurement of leaf PM deposition in the Bosco Mesola Reserve.(Source: Esri - World Imagery Map, 2023).

effects, trees were sampled on four 100 m transects along the woodland borders. Moreover, a further sampling station was placed in the central zone to serve as a comparison between the outer and inner layers of the woodland (Fig. 2). The sampling stations were chosen amongst the reachable portions along the designated sides of the forest. The sampled points were almost exclusively covered by xerophilic habitats dominated by *Q. ilex* and transitional zones between xerophytic and mesophilic habitats with *Q. ilex* and *C. betulus*. These are the most frequent ecosystems in Bosco Mesola woodland and therefore are well representative of the whole Reserve. Three sampling points were established at 0, 50 and 100 m from the border of each of the four major sides of the forest, along perpendicular lines. Two tree specimens were sampled at each point and two more at the fifth inner sampling area at the Reserve center. *Q. ilex* and *C. betulus* were among the most abundant species in the inner area, leading to the decision to sample only these two species to increase data comparability. Outer branches were cut from two opposite sides of each tree's crown at a height >5 m to avoid effects due to particle resuspension from the ground. The mean leaf area per sample was 588 cm^2 (min 475, max 1130 cm^2). Samples were stored in plastic bags and brought to the laboratory for PM quantification.

Particulate matter accumulated on the leaves' surface was retrieved by washing the leaves in water and filtering the resulting solution through filters of progressively smaller pores. Each side of the leaves was carefully hand-washed in 500 ml of micro-distilled water. Washed leaves were subsequently scanned to measure the leaf area with the ImageJ software (Schneider et al., 2012). The solution was then filtered in a plastic sieve (100 μm pore size) to remove large sample residues and then forced through filters using a vacuum filtration system. The different PM fractions were removed using filters with porosity of 10–13 μm (cellulose filters, Filter-Lab 1250, FILTROS ANOIA, S.A. Barcelona), 2.5 μm (cellulose filters Whatman 42, GE Healthcare Life Sciences) and 0.2 μm (nitrocellulose FAVS 0.2). All filters were dried in an oven (Argo Lab TCF120 Plus) at 50 °C for 72 h before and after the vacuum filtration and then stabilized in glass boxes for 1.5 hours, before being weighed with electronic precision balance (precision 0.0001 Crystal 100 CAL, Gibertini). The difference between the first and second weights expresses the sum of PM deposits on the analyzed amount of leaves of the same sample. The $PM_{0.2–2.5}$ load was assumed to be representative of total PM2.5, while PM_{10} loads were obtained by summing the $PM_{0.2–2.5}$ and $PM_{2.5–10}$ size fraction loads. The results of PM accumulated at the whole leaf were then normalized by dividing the PM mass by the reference leaf area and expressed in μg cm^{-2}.

The data were then subjected to one-way ANOVA to test potentially significant differences in PM accumulation along and between transects, as well as between transects and the inner part of the forest and between the two sampled species.

The seasonal LAI was computed using Level-2A Sentinel-2 products, which provide Bottom Of Atmosphere (BOA) reflectance, within the biophysical processor module of the Sentinel Application Platform (SNAP), freely provided by the European Space Agency (European Space Agency, 2018). We processed one image per season; the days of acquisition of the images are 2021/01/13, 2021/03/24, 2021/08/11, and 2021/10/27. The SNAP biophysical processor is based on a pre-trained artificial neural net and makes use of eight spectral bands as well as other information like solar zenith, viewing zenith, and relative azimuth angles (Weiss and Baret, 2016). As a result, we obtained four 10 m resolution rasters (one for each season) reporting the estimated LAI values within Bosco Mesola.

O_3 absorption by vegetation was estimated following the approach proposed by Manes et al. (2016, F. 2012) and Fusaro et al. (2017). Ozone is known for being strongly associated with the presence of solar radiation, with the highest concentrations during hot periods (Calfapietra et al., 2013); therefore, its removal was only computed for the period ranging from the beginning of April to the end of September, when solar radiation and hot temperatures are more likely to occur.

We first calculated the instant stomatal O_3 flux (FO_3), that is, the amount of O_3 instantly absorbed through the stomata. To do so, we applied the following equation:

$$FO_{3(i,p)} = gs_{(i)} \times [O_3]_{(i,p)} \times 0.613 \quad (5)$$

where *gs* is the mean seasonal stomatal conductance of vegetation to water vapor $\left(\frac{mol\ H_2O}{m^2 * s}\right)$, retrieved from Fusaro et al. (2015), *[O₃]* is the mean seasonal Ozone concentration, computed by collecting hourly data from the closest ARPA (Regional Environmental Protection Agency) monitoring station; 0.613 is the diffusivity ratio between Ozone and water vapor, *i* and *p* indicate day and location, respectively. Subsequently, $FO_3(i,p)$ was integrated over the spring and summer months, to estimate the cumulative amount of O_3 which is seasonally removed. We applied the following equation:

$$FO_{3cum(p)} = \left(\sum_{i=1}^{n} FO_{3(i,p)} \times Ph \times \frac{1}{R} \right) \quad (6)$$

where *n* is the number of days, which was set equal to 183; Ph is the photoperiod, which was assumed to be equal to eight hours per day, expressed in s. The stomatal flux is generally equal to roughly 30 % of the total O_3 flux (F. Manes et al., 2012).Therefore, in order to include both stomatal and non-stomatal O_3 absorption, we adjusted our estimate using the *R coefficient,* which is the stomatal/total O_3 flux and is equal to 0.3 (F. Manes et al., 2012).

Finally, the monetary value of air quality regulation service was evaluated based on externality values, an estimated social cost of air pollution that is not included in the market price, including the detrimental effect on human health, the environment, and manufactured materials (EEA, 2020). The externality values are equal to 107,384 € Mg^{-1} and 17,110 € Mg^{-1} for 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 (European Environmental Agency, 2020). The overall monetary value was computed by multiplying the monetary value of each Mg of pollutant with the total Mg of pollutant actually removed by the vegetation.

2.2.2. Climate regulation

Photosynthetic organisms sequester carbon dioxide from the atmosphere and store it in living biomass and soil (Lal, 2008), thus contributing to climate change mitigation. Carbon storage was assessed by accounting for aboveground and soil carbon pools. The aboveground carbon pool was computed using mean aboveground biomass data for the whole Reserve obtained by *Reparto Carabinieri per la Biodiversità*.

$$C = (M \times A \times 0.47) + (C_s \times A) + (M \times 0.35) \quad (7)$$

where *C* is the total carbon stored (Mg), *M* is the mean aboveground biomass per area (Mg ha^{-1}), *A* is the forested area (ha), 0.47 is the carbon density coefficient (IPCC), 0.35 is the root-to-shoot ratio for temperate forests (Penman et al., 2003) and *Cs* is the soil organic carbon content, derived by clipping the Reserve boundaries on the soil carbon map developed by the Regional Environmental Agency (Mg ha^{-1}). It has to be highlighted that, unlike other ESs considered in the study, the climate regulation service is not accounted for as an annual value, since not expressing a dynamic contribution to climate change mitigation (i.e. carbon sequestration), rather it represents a static natural capital stock that should be preserved over time.

Monetary values of carbon pools were estimated by multiplying biophysical values by the mean annual carbon credit value (77.66 € t^{-1}) of the European Union's Emissions Trading Scheme for the year 2021.

2.2.3. Bioenergy and households' heating from woody biomass

Management activities in the Bosco Mesola Reserve require pruning and cuts to avoid fires and fallings, and to optimize tree regeneration. Data for firewood production, bioenergy generation and heating, were provided by *Reparto Carabinieri per la Biodiversità*.

The resulting wood is used for bioenergy purposes in either industrial energy production or destined for local households' heating systems.

The annual industrial energy generation (*E1*; MWh yr^{-1}) was estimated as follow:

$$E1 = E \times L1 \tag{8}$$

where E is the wood energy content (MWh t^{-1}) and *L1* is the annual amount of wood destined to industrial bioenergy production (t yr^{-1}).

The same goes for annual energy of households' heating systems (*E2*; MWh yr^{-1}):

$$E2 = E \times L2 \tag{9}$$

where *L2* (t yr^{-1}) is the annual amount of wood destined to households' heating.

The monetary value of the bioenergy thus provided by the Reserve (*V3, V4*; € yr^{-1}) is based on the market cost of energy for industries (*c3*) and for households (*c4*), equal to 0.3363 and 0.276 € kWh^{-1}, respectively:

$$V3 = c3 \times E1 \times 1000 \quad V4 = c4 \times E2 \times 1000 \tag{10}$$

2.2.4. Eco-tourism

Vegetated and aquatic habitats and several species living in the Reserve attract visitors as a source of cultural services. The Reserve is open to public visits from March to October and can be accessed in multiple ways, by both walking and cycling. The eco-tourism service was assessed by collecting data on visitor entrances and bike rentals and computing their respective monetary values, as provided by Reparto Carabinieri per la Biodiversità. A limited area of approximately 100 ha is accessible by walking or bicycle upon the payment of a 1 € ticket. The majority of the Reserve is only accessible with tours guided by rangers or environmental guides through the purchase of a 3 € ticket. A mean bike rental cost of 8 € by the nearby bike-rent facility was assumed. A cycling trail running along the shoreside of the Reserve can be accessed free of charge and therefore it was not considered for monetary evaluation.

3. Results

ES biophysical and monetary assessments are reported in Table 2. The overall mean annual monetary value is 10.4 M€ yr^{-1} (9816 € ha^{-1} yr^{-1}). Air quality regulation accounts for 10.2 M€ yr^{-1} (98% of the total value), 9.7 M€ yr^{-1} of which is due to airborne PM_{10} removal (93.4%). Additionally, climate regulation by carbon storage was equal to an absolute value of 7.2 M€, further increasing the importance of the Reserve as a provider of regulating services.

Table 2
Biophysical and monetary values of the selected ecosystem services provided in the Bosco Mesola Reserve.

Ecosystem service	Ecological function	Biophysical value	Monetary value (€ yr^{-1})
Air quality regulation	PM removal	90.37 kg yr^{-1}	9704,292
	Ozone removal	30.54 kg yr^{-1}	522,539
Climate regulation*	Carbon storage	92,776 t C	7204,965
Total Regulating			***10,226,831***
Bioenergy	Firewood production	430.5 kWh yr^{-1}	144,777
Households' heating		5.24 kWh yr^{-1}	1446
Total Provisioning			***146,223***
Eco-tourism	Presence and access to natural features	12,000 tickets yr^{-1} + 300 bike rentals yr^{-1}	12,600
Total Cultural			***12,600***
Total annual value			**10,385,655**

* not included in the total annual value (expressed in €).

3.1. Seasonal leaf area index and regulating services

Mean annual PM_{10} and O_3 removals were modeled based on the seasonal LAI. The latter showed a significant seasonal pattern (Fig. 3), ranging from a minimum mean value of 0.92 m^2 m^{-2} in winter to 2.23 m^2 m^{-2} observed in summer for the whole Reserve (Table 3). The amount of PM deposited on leaves was experimentally measured to model PM_{10} removal. The sampled trees belonged to *Q. ilex* (78%) and *C. betulus* (22%) species, retrieved from 13 sampling points. The mean PM_{10} and $PM_{2.5}$ mass deposited per leaf unit were 21.35 (±1.98 St. Err.) and 2.75 (±0.28 St. Err.) μg cm^{-2}, respectively. The mean daily PM air concentration values in the 13 previous dry days were 18.23 and 11.38 μg m^{-3} for PM_{10} and $PM_{2.5}$, respectively. Interestingly, the one-way ANOVA test did not highlight significant differences (p-value >0.05) within and among transects, nor between species. Hence, single *Vd* values of 0.9468 cm s^{-1} for PM_{10} and 0.1218 cm s^{-1} for $PM_{2.5}$ were obtained according to eq. 3 and applied for modellingPM removal in the whole Reserve. Overall, the Bosco Mesola Reserve removed 90.37 t of PM_{10} during the year 2021, of which 11.67 t of $PM_{2.5}$. Although air PM pollution levels were higher in winter, PM_{10} removal was larger in summer, when a higher LAI was available. Such a pattern was not observed for $PM_{2.5}$ (Table 3). The total O_3 removal during the year 2021 was 38.88 t, with larger removal quantities observed in spring when air O_3 pollution levels were higher.

3.2. Climate regulation

The climate regulation service was evaluated by estimating the amount of carbon currently stored in the Reserve. This value does not contribute to the annual contribution of the study area to human well-being. According to the available data, the aboveground biomass of the Reserve is 85.5 t ha^{-1}, corresponding to 40.18 t C ha^{-1}, being the most important carbon pool, followed by soil (33.44 t C ha^{-1}) and below-ground biomass (14.06 t C ha^{-1}). Overall, the total carbon storage is 92,776 t C (87.69 t C ha^{-1}), corresponding to a monetary value of 7.2 M€.

3.3. Bioenergy and households' heating

An average of 106.3 t of wooden material are exported annually from the Bosco Mesola Reserve, resulting from environmental management practices. The larger part (105 t yr^{-1}) is purposed to industrial bioenergy generation for energy production of 430.5 MWh yr^{-1}. A lesser amount (1.277 t yr^{-1}) is destined to a local community for heating, corresponding to an energy amount of 5.24 MWh yr^{-1}. In accordance with energy prices for industries and households, the monetary values for industrial bioenergy generation and households' heating are, respectively 144,777 € yr^{-1} and 1446 € yr^{-1}.

3.4. Eco-tourism

A total mean of about 12,000 ticket entrances was recorded annually, of which 2000 were free for schools and local inhabitants. The remaining 10,000 entrances occurred upon the payment of a ticket, 1900 of which with environmental guides. The estimated bike rentals were about 300 per year. Additionally, a further rough estimate of 12,000 free entrances per year occurs through the pedestrian corridor located at the southern part of the Reserve. However, the latter were not included in the monetary assessment. Overall, even though a precise quantification was not possible, it can be estimated that the eco-tourism service in the Bosco Mesola Reserve accounts for a total mean of 12,600 € yr^{-1}.

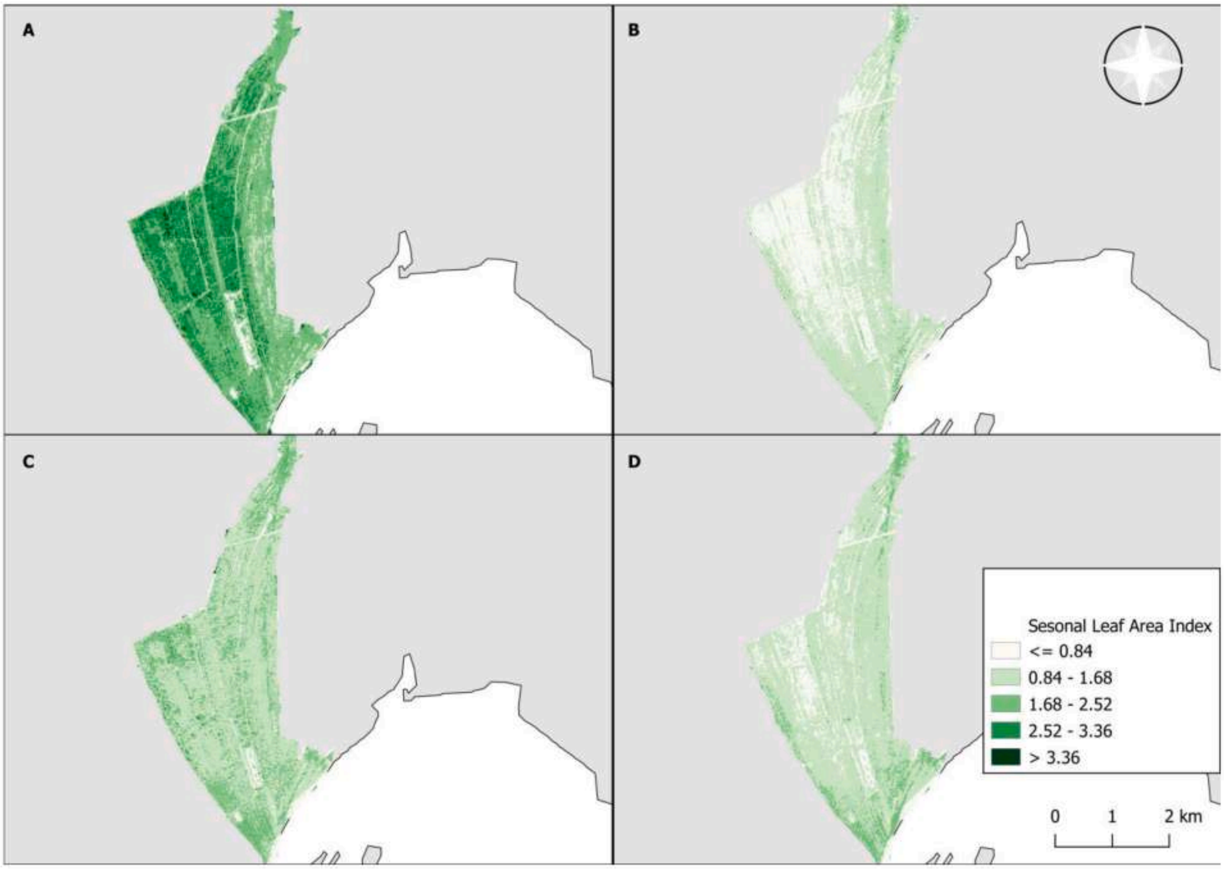

Fig. 3. Leaf Area Index (LAI) seasonal pattern obtained by Sentinel-2 data. A - Summer; B - Winter; C - Autumn; D - Spring.

Table 3
Seasonal and annual $PM_{2.5}$, PM_{10} and O_3 removal (absolute and per unit area) modelled on seasonal LAI.

Season	Mean LAI m^2 m^{-2}	$PM_{2.5}$ removed t	kg ha^{-1}	PM_{10} removed t	kg ha^{-1}	O_3 removed t	kg ha^{-1}
Spring	1.17	1.69	1.60	13.17	12.45	24.78	23.42
Summer	2.23	3.29	3.11	31.53	29.80	14.10	13.33
Autumn	1.48	3.29	3.11	24.56	23.21	-	-
Winter	0.92	3.40	3.21	21.11	19.95	-	-
Total		**11.67**	**11.03**	**90.37**	**85.416**	**38.88**	**36.75**

4. Discussion

4.1. ES quantification

The results demonstrate that the Reserve remarkably supports human well-being, mainly by regulating air quality and climate, thus representing an extraordinary source of regulating services. Overall, the Bosco Mesola Reserve shows high ES values when compared with other studies providing monetary values of other forest ecosystems. The total value per ha (9816 € ha^{-1} yr^{-1}) exceeds the mean annual value of 3137 US$2007 (equals to 3475 €2021; inflation rate €2021 = 1.178, exchange rate 1$ = 0.94 €) reported by Costanza et al. (2014) for temperate forests, yet falling within the range values reported (308 – 18,176 €2021). Nonetheless, such value exceeds the mean values reported in the more recent meta-analyses of primary studies, which also demonstrate that total ESs values are influenced by different drivers, including GDP-per-capita and valuation method employed. Taye et al. (2021) reported a mean ESs value of 4397 €2021 ha−1 yr−1 for temperate forests, while Grammatikopoulou and Vačkářová (2021) found lower values (1134 €2021 ha^{-1} yr^{-1}), confirming that regulating services contribute mostly to the total value. The differences between previous studies and our findings are mainly due to the contribution of air quality regulation service to the total annual value, thus arising the issue related to the identification, quantification and conservation of ESs with no direct market value. In fact, while fuelwood production and eco-tourism generate direct incomes to the providers, pollutants removal, as well as carbon storage, have indirect, yet large, monetary value, whose socio-political and applicative fields have immensely different impacts. Indeed, by adopting a VOLY-based approach, the monetary evaluation of pollutants removal is based on the impact of such pollutants on human health, whereas the other ESs are evaluated following a market-based approach. Therefore, as a consequence of the great importance given to human health, which translate in high VOLY values, the monetary evaluation of pollutants removal results to be significantly higher compared to the other ESs

This gap could be explained by the paucity of existing studies concerning air pollutant removal by forest ecosystems, as well as by the different bio-physical and monetary valuation methods adopted, which reduce potential comparability. Moreover, as demonstrated by Gaglio et al. (2022), current models may underestimate the PM removal performed by vegetation, thus leading to lower monetary values. Our assessment of PM removal is based on an experimentally measured *Vd*, to increase the reliability of estimates, also investigating possible, but not confirmed, effects due to distance from edges, location and species. Although the four sides of the Reserve are exposed to pollution sources that vary in intensity and typology, no significant differences in terms of PM accumulation were observed. It is possible that the wind speed during the previous dry days was sufficiently constant to not result in substantial variations of resuspension phenomena and therefore of the calculated *Vd*. In fact, since PM resuspension is favored by wind speed variations (Wang et al., 2013), the exposition of leaves to constant wind speed may explain the lack of differences among transects. No significant differences were observed within transects as well, despite the decline of air PM concentration and those deposited on leaves were expected at increasing distances from forest edges, according to literature (e.g. Cavanagh et al., 2009; Popek et al., 2015). This may be explained by the seasonality of nearby point source emissions (e.g. agricultural activities), which could be not active during the sampled period, and/or by their distance from the Reserve borders, leading to the mitigation of the directional gradient of PM deposition. Spatial differences in air PM concentrations among the Reserve sides are likely to be observable in winter, when, however, deciduous species do not contribute to air quality regulation. Lastly, the limited number of *C. betulus* samples could justify the absence of differences in PM deposition between the two sampled species. However, the lack of significant effects was confirmed also by comparing *Q. ilex* and *C. betulus* in sampling points where both species occur. Although it is demonstrated that evergreen and deciduous tree species perform differently (Muhammad et al., 2019; Muresan et al., 2022), some studies suggested that the removal capacity of *Q.ilex* in terms of PM_{10} and $PM_{2.5}$ is comparable to those of deciduous species (Gaglio et al., 2022; Vigevani et al., 2022) in accordance with this study.

Ozone removal is another important function that concurs to air quality regulation. Even though the amount of ozone removed annually is approximately one third of the PM removed, its monetary value accounts for only 5% of the total regulating ES value. This is due to the lower monetary value per unit of pollutant compared with those of PM, which can in turn be explained by the less concerning health impact of O_3 compared to PM (EEEA, 2021), and to the restricted temporal range of ozone removal to summer and spring seasons. In fact, the ecological functions underpinning air quality regulation show a marked seasonality, due to a combination of leaf area and air pollutant levels.

Despite the higher air PM pollution levels recorded in winter, PM_{10} removal is higher in spring, because of the higher LAI. Contrarily, ozone removal peaks in summer, when the lowest value for PM removal was observed. This pattern underlines the importance of the coexistence of both deciduous and evergreen vegetation for air quality regulation.

Climate regulation, here intended as carbon storage is another notable regulating service provided in the study area. Since the ecosystem represents the climax condition of the regional coastal area, vegetation and soils of Bosco Mesola Reserve absorb significant amounts of CO_2 from the atmosphere to store in biomass. The results (87.7 t C ha^{-1}) are coherent and slightly higher than the average amounts observed in other Italian Parks for general forested areas (81.21 t C ha^{-1}) and specifically for mixed forests dominated by holm oak (77.76 t C ha^{-1}) (Marchetti et al., 2012). Provisioning and cultural services denote minor monetary values when compared with regulating services. In fact, as the area is devoted to biological conservation, wooden materials destined for energy purposes, either industrial or private, are restricted to those deriving from pruning and selective cuts. Similarly, fruition for tourism and education is limited by the requirements for habitats and species protection. It was demonstrated that biological conservation has synergies with regulating services in forest ecosystems while showing trade-offs with firewood production and to a lesser extent with cultural services (Löf et al., 2016). Conversely, forests exploited for wood harvest show a reduced provision of other ESs (Galicia and Zarco-Arista, 2014; Uddin et al., 2013). In general, the conservation option supplies the most benefits compared to the selective use of forests (Ninan and Inoue, 2013). Nonetheless, ESs with lower monetary values need to be valorized and properly considered in the decision-making process.

4.2. Contribution to sustainable development goals

Although air quality regulation was by far the dominant ES in the monetary analysis, the whole set of ESs provided by Bosco Mesola Reserve may have a strategic importance for sustainable development. In this sense, the study shows that environmental conservation offers opportunities for the synergistic achievement of different SDGs with local and global relevance, confirming the observations of Wood et al. (2018), who found that habitat and biodiversity maintenance is a key ES for SDGs and targets. The significance of the present analysis goes beyond the monetary dimension of ESs, and sheds light on the comprehensive importance of nature-based solutions for the sustainable land management. It is worth mentioning that considering the ESs contribution to the SDGs of Agenda 2030 is not in contrast with the monetary quantification included in the SEEA framework. In fact, the SDG 15, target 15.9.1.b) explicitly requires the "integration of biodiversity into national accounting and reporting systems, defined as implementation of the System of Environmental-Economic Accounting".

Overall, because of its indisputable conservation value, the Reserve directly supports SDG 15 (Life on land). Moreover, its ponds and canals have a local relevance on the achievement of SDGs 14 (Life below water) and 6 (Clean water and sanitation). Air quality regulation strongly supports the SDG 3 (Good health and well-being) by reducing premature deaths and illnesses and specifically with respect to the target 3.9, which refers to the mortality rate caused by air pollution. This aspect has paramount importance for European citizens, who are chronically exposed to high pollution levels. In fact, according to the EU Environmental Agency, air pollution is the largest environmental health risk in Europe. In particular, $PM_{2.5}$ and O_3 caused, respectively 238,000 and 24,000 premature deaths in 2020, of which 52,000 and 5000 in Italy (European Environmental Agency, 2022). Air quality regulation is even more strategic in the Po plain, one of the major air pollution hotspots in Europe.

Climate regulation by carbon storage is another key ESs for reaching SDGs. It is strongly associated with the achievement of the SDG 13 (Climate action), thus underlining the Reserve contribution at the global scale. While the costs for reducing the GHG emissions often burden local communities, the capacity of natural ecosystems to sequester carbon dioxide from the atmosphere represents a cost-effective climate mitigation measure, with several positive side effects for the provision of other ESs (Wood et al., 2018).

Households' heating and industrial bioenergy generation contributes to SDG 7 (Affordable and clean energy) and, to a lesser extent, SGD 11 (Sustainable cities and communities). Woody residues represent a highly sustainable supply chain for bioenergy, since they avoid impacts and conflicts for land use that are typically observed in the case of dedicated energy crops (Gissi et al., 2017, 2016; Tamburini et al., 2020). The Reserve also guarantees a constant source of wood for households' heating, increasing the environmental and socioeconomic sustainability of the local community and overcoming the concerns related to the scattered distribution of residues on the landscape (Gaglio et al., 2021).

The contribution of the Reserve to human well-being also encompasses cultural services. Eco-tourism and other forms of recreation and experiences in nature areas increase cognitive functions and mental health (Bratman et al., 2019, G.N. 2012) and are negatively correlated with antidepressant prescriptions (Marselle et al., 2020), thus concurring to the achievement of the SDG 3 (Good health and well-being). The Reserve also supports SDGs 4 (Quality education), being visited by scholars, and 8 (Decent work and economic growth), as it provides job opportunities for environmental guides and other related activities (e.g. bike rental).

4.3. Limitations of ES evaluation and future research directions

The inclusion of ESs in environmental planning and governance calls for two major challenges. On one hand, a reliable ES assessment requires the use of primary data and modeling to evaluate complex ecological functions (e.g. air pollutants removal by vegetation). While primary data can be difficult to obtain, models are based on assumptions and simplifications of complex ecological processes. On the other hand, there is a need for the development of mechanisms linking ES evaluation with

Agenda 2030, and more generally to underline nature-people relationship.

The ES evaluation presented in this study provides significant information for environmental managers, but some limitations should be considered. For instance, the PM removal model does not take into account resuspension and incomplete washing phenomena that significantly affect particulate deposition on leaves (Wang et al., 2015). Sebastiani et al. (2023) have recently shown that, during summer, the satellite-derived LAI reflects the field-measured LAI with moderate accuracy, and tends to saturate for values above 5; therefore, the output of the model has likely been affected by such an uncertainty. Moreover, the experimental measures of the *Vd* reflect only one field survey; additional samplings could highlight seasonal differences in space and time that were not observed in this study. Similarly, the ozone removal model considers a single mean stomatal conductance for the entire leaf area, missing to consider differences in space and time and omits to compute emissions of biological volatile organic compounds (BVOC). In fact, BVOC, released by plants to mediate interactions with animals and other plants (Finetti et al., 2021), can react in the atmosphere leading to ozone formation (Calfapietra et al., 2013). Future studies should consider the net balance between ozone formation and removal by trees. The carbon pools considered in carbon storage estimates are also affected by limitations. Soil carbon maps do not consider the humic layer of soil, an important carbon pool (Doane et al., 2003), as well as litter material. The belowground biomass was estimated using a mean root-to-shoot ratio from the literature, rather than precise quantifications. Moreover, carbon sequestration (i.e. carbon flux from the atmosphere to the ecosystem through photosynthetic processes) was not considered in the analysis. The Reserve also provides several cultural ESs that were not considered in this analysis and whose evaluation in monetary terms remain difficult. Finally, the analysis should be extended at the landscape scale to capture additional ES, e.g. pollination, pest control and water regulation, in order to better describe ES flows along spatial gradients.

Concerning the monetary evaluation, the dominance of air quality regulation on the total annual monetary value may be partially due to the evaluation method, based on externality values related to human health (i.e. avoided damage costs). On the other hand, future research and solutions are needed for including ESs in nature governance, particularly those with non-market value, as in the case of air quality regulation. In this sense, Payment for Ecosystem Services (PES) schemes represent suitable instruments, either in the form of “genuine” or “PES-like” mechanisms (Gaglio et al., 2023). Nonetheless, the monetization of nature is subjected to criticisms, as risking to reduce nature to a unique monetary and utilitarian dimension, particularly when focused on provisioning and cultural services (Krozer et al., 2020).

5. Conclusions

Remnant forests are natural areas with exceptional ecological value, particularly when located on intensively exploited landscapes. The EU Biodiversity Strategy to 2030 calls for the need for strict protection of such ecosystems, as well as for the increase of their ecological quality and resilience. The quantification of ESs provided by protected forests is necessary to support environmental managers towards the achieving of SDGs foreseen by the Agenda 2030. Notwithstanding, the contribution of remnant forests to human well-being is still poorly studied. This work provides an assessment of the main ESs provided by the Bosco Mesola Reserve, a protected remnant forest located in the river Po delta (Northern Italy) which has undergone persistent land reclamation over the last century and is nowadays mostly covered by intensively managed croplands. The approach encompasses both biophysical and monetary assessment, coherently with the SEEA EA framework, integrating experimental data, modeling and information obtained from environmental managers. Such methodology can be exported to other case studies where ES assessment requires the combination of multiple methods and data sources.

The analysis demonstrated that the Reserve is an extraordinary source of regulating services, such as air quality regulation from air pollutants and climate mitigation, thus providing a remarkable contribution in contrasting the ongoing Climate Change. With the monetary evaluation, we provided a reference value that will certainly be useful for stakeholders and policymakers in orienting new conservation and land management strategies and will also serve as a benchmark for comparison to upcoming studies. Future researchers for specific case studies should be coherent with the SEEA EA framework, in order to provide a ground for analyses at wider scales, and integrate different assessment methods to capture a comprehensive range of ESs.

CRediT authorship contribution statement

Mattias Gaglio: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Alexandra Nicoleta Muresan:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Alessandro Sebastiani:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Davide Cavicchi:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Elisa Anna Fano:** Conceptualization, Validation, Writing – original draft, Supervision. **Giuseppe Castaldelli:** Conceptualization, Validation, Writing – original draft, Supervision.

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.

Data availability

Data will be made available on request.

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