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RESEARCH ARTICLE

Afforestation priority for multiple objectives at national scale: Italy as a case study

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Abstract

Introduction: Afforestation is increasingly recognized as a key strategy to address climate change and ecological degradation, offering multiple ecosystem services. However, strategic planning is needed to ensure that afforestation actions are ecologically effective and economically efficient by targeting areas where ecosystem service provision is most significant.

Objectives: In this study, we provide a workflow to prioritize afforestation areas at national scale tailored to four distinct ecosystem service goals: ecological connectivity, human health, climate mitigation, and water regulation.

Methods: Using Italy as a case study, we applied goal-specific analysis to areas considered suitable for afforestation, integrating geospatial datasets of environmental and social factors. For each objective, spatial indicators were combined into a priority map at 1 km resolution, subsequently aggregated into composite maps. The top 20% priority areas for each objective were identified to inform national and regional planning.

Results: High-priority areas to improve ecological connectivity were focused around urban centers and extensive agricultural plains. Water regulation benefits were most relevant in urbanized and vineyard landscapes, while urban areas also emerged as priorities for human health. Climate mitigation potential was highest in moist temperate and mountain regions. Overlap among goals was limited, revealing significant trade-offs across ecosystem services.

Conclusions: The workflow provides a replicable approach to identify goal-specific afforestation priorities across diverse landscapes. It supports coordinated strategies to enhance ecosystem service provision and restoration effectiveness at national and regional levels.

Implications for Practice: Goal-specific afforestation planning can maximize ecological benefits, cost-effectiveness, and policy impact. By identifying priority areas for different ecosystem services, the workflow helps practitioners target interventions where they yield the greatest benefits. The identification of urban and agricultural zones as key opportunities for multifunctional interventions supports the integration of urban forestry and agroforestry into restoration strategies. The limited overlap among goals underscores the need to explicitly balance trade-offs when designing multi-objective restoration programs. The workflow is readily adaptable to other European countries, thanks to the availability of large-scale spatial datasets, offering a practical decision-support tool for policymakers and practitioners engaged in forest landscape restoration.

Key words: afforestation, climate mitigation, ecological connectivity, ecosystem services, spatial priority, urban forestry

Introduction

Forests provide numerous ecosystem services (ESs) supporting human well-being and environmental sustainability. Alongside more traditional provisioning ESs, such as wood and non-timber forest products (Clason et al. 2008) and cultural services (Paracchini et al. 2014), increasing attention has been given to conservation of biodiversity and regulating services such as carbon sequestration, improvement of air quality, temperature reduction, water regulation (Thompson et al. 2011; Decocq et al. 2016; Liang et al. 2016; Mori et al. 2017). Afforestation can play a crucial role contributing to such goals. In recent years, afforestation has sparked the interest of public and private sectors worldwide, both promoting ambitious tree planting initiatives (e.g. IUCN 2016) with the aim of restoring biodiversity and improving the provision of multiple ESs (Chazdon et al. 2016; Waring et al. 2020). These objectives are aligned with key European policy frameworks, including the EU Biodiversity Strategy

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for 2030 (European Commission 2020), the EU Forest Strategy for 2030 (European Commission 2021), and the EU Climate Law (European Parliament and Council of the European Union 2021). For instance, the EU Biodiversity Strategy includes a commitment to plant at least 3 billion trees by 2030.

Forest ES provision is influenced not only by species choice, plantation design, and management, but also by site-specific environmental conditions (Baskent et al. 2020; Pérez-Silos et al. 2021). Several studies highlighted how plantations without an appropriate strategy can lead to unfavorable impacts (Farley et al. 2005; Elmarsdottir et al. 2008; Doelman et al. 2020). Afforestation without considering site-specific characteristics or the needs of a certain area, can be ineffectual or even counterproductive for ESs. For example, the massive afforestation on the Chinese Loess Plateau, implemented without considering soil and climate conditions, caused water table decline and soil erosion (Jiang et al. 2016). Furthermore, afforestation without considering soil carbon saturation or the previous land use, could lead to soil carbon losses instead of gains (Czimczik et al. 2004). A further example concerns places where afforestation implies losses of biodiversity, such as in traditionally managed open grasslands, where transition to forested areas can lead to a reduction in species richness and correlated provision of ESs (Prangel et al. 2023). For these reasons and given the limited funding, efficient planning requires identifying areas to be afforested to maximize benefits, avoid unintended consequences, and optimize costs. To identify priority areas, the first step should lay in defining one or more goals for afforestation; an effective approach then involves the use of analysis that considers both environmental and socio-economic factors (Sun et al. 2022; Fahrudin et al. 2024) to maximize the pursuit of such goals.

Several recent studies have proposed national or large-scale assessments of afforestation potential, focusing on single or multiple ESs (Bradfer-Lawrence et al. 2021; Baggio-Compagnucci et al. 2022; Burke et al. 2023), and emphasizing the need for spatially explicit evaluations to support strategic planning. In this context, our study contributes by integrating four distinct afforestation goals within a reproducible framework based on spatial data, enabling scalable and transferable applications to other European countries.

The main objective of this research is to prioritize afforestation areas based on four specific ESs (ecological connectivity, human health, climate mitigation, and water regulation), aligned with global and national sustainable development goals, thereby offering a more comprehensive and targeted approach to afforestation planning. Our findings allow us to generate goal-specific maps of afforestation priorities at the national scale, as well as synthesis maps to provide an integrated overview of afforestation priorities considering all the goals together. The specific goals we consider herein are:

(a) Ecological connectivity

Ecological networks are a strategic tool for biodiversity conservation (Jongman 1995). The importance of ecological connectivity and urban challenges highlight the need for large-scale planning to define a targeted planting plan, assessing where it is most strategic to invest efforts and resources (Kremer et al. 2016; Di Pirro et al. 2021).

(b) Human health

The compound effects of climate warming and Urban Heat Island effect (Fini et al. 2017), pose a significant threat to human health, especially for urban vulnerable populations (Heaviside et al. 2017). Air pollution also represents a significant threat to public health, as WHO data (World Health Organization 2022) indicate that 99% of the global population breathes air with pollutant concentrations exceeding WHO recommended limits. Urban forests can improve air quality by removing atmospheric pollutants, and reduce air temperatures through shading and evapotranspiration (Brack 2002; Nowak et al. 2006; Yan et al. 2018).

(c) Climate mitigation

Forest restoration can make a major contribution to climate change mitigation through carbon sequestration (IPCC 2023). Carbon sink potential depends on tree species and age, climate, soil type, water and nutrient limitations (IPCC 2022). Both the biomass of new trees and the accumulation of carbon in the soil, which is much more long-lived than the aboveground carbon sink, contribute to reducing atmospheric greenhouse gas concentrations.

(d) Water regulation

Afforestation is a key countermeasure adopted where the land cover change exerted a strong alteration on catchment hydrology (Blöschl et al. 2007; Pattison & Lane 2012). Planting trees helps reduce run-off, intercepting rainfall, altering transpiration rates, increasing the rainfall infiltration and saturated soil hydraulic conductivity, and prolonging the local water storage over time (Buytaert et al. 2007; Silveira et al. 2016; Murphy et al. 2021). With these perspectives, the current challenge is to identify the location of afforestation to maximize the mitigation of negative consequences of land use change and climate change.

We selected Italy as a representative and complex case study, given its unique combination of geographical, socio-economic, and environmental characteristics.

Case Study

Italy's territory (Fig. 1), spanning approximately 300,000 km^2, is 36.7% covered by forests (Gasparini et al. 2022). Similar to other European countries, Italy exhibits a contrasting spatial pattern: forest expansion in mountainous and marginal zones due to the abandonment of traditional agricultural and pastoral activities (Sallustio et al. 2015), alongside increasing urbanization of lowlands and coastal zones (Romano & Zullo 2014).

Today, urban areas in Italy cover 7% of the national territory, among the highest in the EU, and continue to expand despite the demographic decline observed in the country (ISPRA 2016). This increasing urbanization poses a serious threat to biodiversity (McDonald et al. 2008), which in Italy is exceptionally rich thanks to its high climatic, orographic, and geological variability (Falcucci et al. 2007). The network of protected areas covers 22% of the country (ISPRA 2024), including over 2600 sites.

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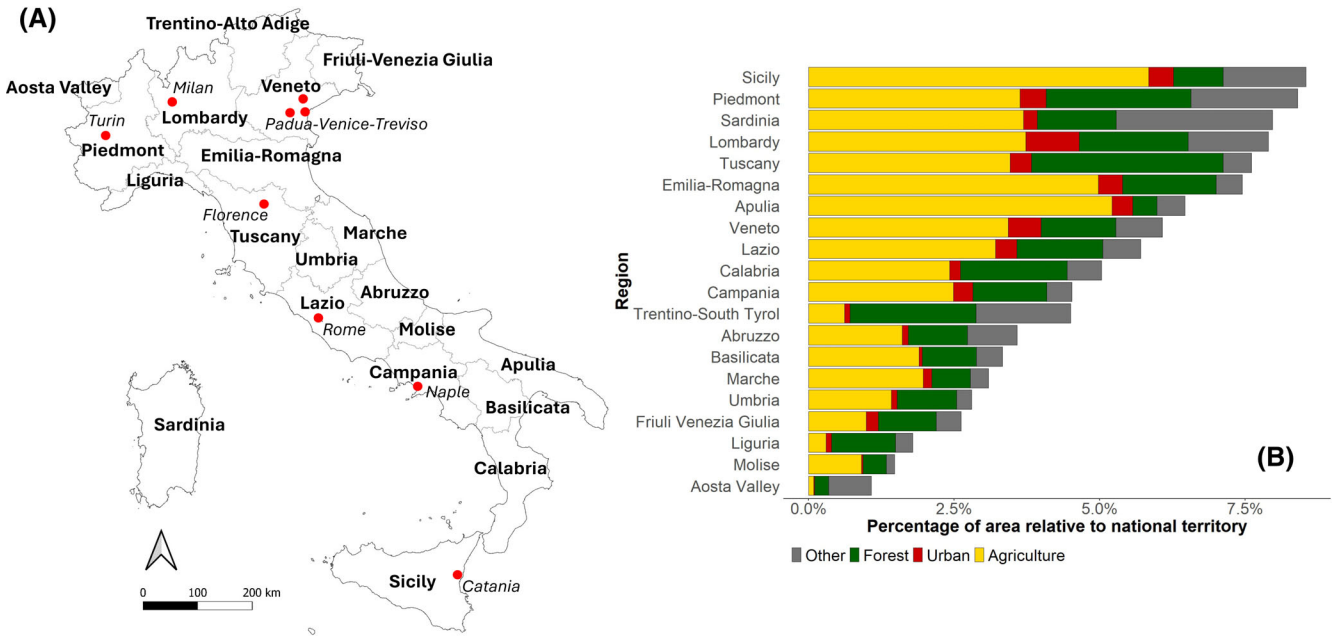

Figure 1. (A) Regions of Italy and some cities mentioned in the text (using MAP01); (B) the bar chart details each region's percentage of surface area relative to the national total. Colors indicate land use categories derived from the Corine Land Cover dataset (MAP02): urban areas (artificial surfaces), agricultural areas, forests, and other land uses.

Urbanization also has significant implications for public health. Although air pollutant concentrations have declined in recent years, they still exceed the WHO recommended limits, particularly in urbanized areas (SNPA 2024a). Climate change is marked by a mean temperature increase of 0.4°C per decade since 1981 (SNPA 2024b) and a decline in average precipitation since 1961–1990, alongside more frequent extreme rainfall and prolonged dry spells (Brunetti et al. 2004; Iannuccilli et al. 2021) with significant socio-economic and environmental impacts (Maxwell et al. 2019; Mateos et al. 2023).

In agreement with European strategies, Italy planned large-scale actions targeting its 14 Metropolitan Cities to plant 6.6 million trees by 2026 (National Recovery and Resilience Plan, PNRR; Italian Government 2021), aiming to combat air pollution, climate change, and biodiversity loss.

These dynamics make Italy an ideal setting to test an afforestation planning approach that integrates multiple objectives and considers specific territorial features. Di Pirro et al. (2022) explored afforestation priorities in Italy based on the analysis of some of their expected benefits (air pollution, thermal stress, and hydraulic vulnerability), but their analysis should be expanded to a broader suite of forests' contributions.

Methods

The analysis and spatial data processing were executed using Geographic Information System (GIS) and Google Earth Engine programming. This study was conducted at a national scale with a spatial resolution of 1 km. All input layers were resampled, when necessary, to a common 1 km^2 grid using bilinear interpolation for continuous variables and mode assignment for categorical ones. Each resulting map, called priority map (PMAP), presents afforestation priority as a score from 0 to 1.

First, we selected suitable areas for afforestation. To do this, we applied a spatial prioritization analysis specific to each of the four afforestation target goals, based on the integration of multiple indicators relevant to each objective (Fig. S1). Each factor is spatially explicit, with data available at the national scale (Table 1).

To identify potentially suitable areas for afforestation, we excluded the following categories: (1) existing forests (from Corine Land Cover 2018, CLC, MAP02 in Table 1); (2) zones above 1600 m a.s.l. (from Digital Elevation Model, DEM, MAP03), in order to exclude areas beyond the upper tree line or with unfavorable climatic conditions; (3) wetlands (MAP02) and protected areas (MAP04), that require site-specific consideration; (4) land uses (MAP02) unsuitable for forest growth, either natural conformation (water bodies, beaches and dunes, rocky surfaces, heaths, glaciers, and perennial snow) or anthropogenic (airports, port areas, road and railway networks); (5) areas with potential non-forest natural vegetation (MAP05). Agricultural areas were not excluded because they could be restored through the creation of hedgerows and the adoption of agroforestry systems as afforestation actions. Urbanized areas were also considered as potentially suitable, as they may contain green spaces undetected at the given resolution, or areas convertible through land use change, and are therefore crucial for achieving the study objectives.

The values resulting from the four composite indicators were all rescaled to a range [0–1]. In the resulting PMAPs, afforestation priority is assigned based on score percentiles. This approach supports territorial decision-making in cases where a

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Table 1. Summary and references of the maps and datasets used in the analyses (the last access to all links is 21 July 2025).

Map Code	*Name*	*Source*
MAP01	Administrative boundaries of Italia and its regions	ISTAT (2025)
MAP02	CORINE Land Cover 2018 (CLC)	European Union's Copernicus Land Monitoring Service Information (2018); Vector: https://doi.org/10.2909/71c95a07-e296-44fc-b22b-415f42acfdf0; Raster: https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac
MAP03	DEM TINITALY	Tarquini et al. (2023)
MAP04	Protected areas—WDPA	UNEP-WCMC and IUCN (2025)
MAP05	Potential Natural Vegetation Map of Italy	Blasi et al. (2017)
MAP06	National Hydrographic Network—dataset	ISPRA (2010)
MAP07	Population density	CIESIN (Center for International Earth Science Information Network)—Columbia University (2018)
MAP08	Air quality	Horálek et al. (2021)
MAP09	Climate dataset—CHELSA V.2.1	Karger et al. (2017)
MAP10	IPCC soil classes	FAO and IIASA (2023)
MAP11	Hydrologic soil groups	Ross et al. (2018)

specific afforestation target (in terms of area) must be met. As an illustrative metric, we also analyzed the spatial distribution of high-priority areas (HPAs), defined here as those exceeding the 80th percentile of the suitability distribution for each afforestation goal.

Ecological Connectivity

Under this goal, we prioritized areas where afforestation can establish or improve ecological corridors or provide stepping stones in highly fragmented zones, thereby strengthening the national ecological network of forest areas. Specifically, we focused on three indicators, analyzed through dedicated maps:

- Fragmentation (F): we assessed the ecological connectivity at each 1 km pixel based on a Least Cost Path (LCP) algorithm (Adriaensen et al. 2003), considering both the shortest distance from existing forests and the degree of ecological resistance ("cost") to animal movement played by the land uses (MAP02) occurring along the path. We assigned the minimum cost per pixel to forest areas and the maximum cost value to highly anthropized areas such as urban fabric, infrastructures, and intensive agriculture (Table S1). The subsequent step involved identifying the least-cost path connecting each pixel with the nearest forest land (MAP02). Pixels with higher cumulative LCP values correspond to areas with lower forest connectivity and higher priority for afforestation. The result was mapped in MAP12.
- Protected areas (PA): we assigned higher priority to sites that have the potential to improve connectivity between protected forest patches. To do so, for each pixel we calculated the sum of the squared Euclidean distances from the centroids of the forested patches in the two nearest protected areas (intersection of MAP02 and MAP04). Since smaller sums imply stronger corridor potential, we multiplied all values by -1 so that larger (i.e. less negative) values would denote higher priority.
- Proximity to watercourses (PW): riparian buffers of variable width (Fischer & Fischenich 2000) act as significant corridors for movement and dispersal (Machtans et al. 1996; Burbrink et al. 1998; Santos et al. 2011). To assign higher priority to ecosystems along watercourse (MAP06), we assigned to all pixels within 1 km buffer from rivers a value of 1, and 0 to all others.

We rescaled all three indices to a range [0, 1] and calculated the afforestation priority P by applying Equation (1).

$$P = F\left(1 + \mathrm{PA} + \frac{\mathrm{PW}}{2}\right), \quad (1)$$

where F serves as primary driver, scaling the combined influence of the other factors, prioritizing afforestation in heavily anthropized areas and penalizing areas close to existing forests, where natural afforestation could occur. PW was weighted at 50% to balance its binary scale against the continuous nature of PA. The result was mapped in PMAP1.

Human Health

In this case the methodology prioritizes areas where a large number of people are exposed to higher health risks, with a focus on temperature and air quality:

- Population density (d): number of inhabitants per km^2 (MAP07).
- Air quality: we considered the concentrations of PM_{10}, NO_2, and O_3, three air pollutants harmful to human health that trees can partially absorb (Yang et al. 2005). Pollutant concentrations were assessed using the maps from Horálek et al. (2021) (MAP08), which provide the annual mean concentration of PM_{10} and NO_2 ($a1$, and $a2$, respectively), and the 93.2nd percentile of maximum daily 8-hour mean concentration of O_3 ($a3$) which is associated with a higher mortality rate compared to the 24-hour average concentration (Yang et al. 2012).
- Temperature: we considered the number of tropical nights (NTN) per year in future climate scenarios as an indicator of health risk (Yavaşlı & Erlat 2024). Since daily data were not available at a national scale as raster maps, we estimated NTN using a nonlinear equation. This approach is largely

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used in the literature for many climatological parameters, such as the Growing degree days above 5°C (Wang et al. 2011; Wang et al. 2016). For every pixel, we calculated NTN as a function of monthly minimum temperature using Equation (2):

$$\mathrm{NTN} = \sum_{i=1}^{12} \left(\frac{nd_i}{1 + 1.382 \times 10^6 \times \mathrm{e}^{-0.7162\, T\min_i}} \right) \quad (2)$$

where nd_i is the number of days in i-th month; $T\min_i$ is the mean monthly minimum temperature for i-th month. This equation was calibrated using daily temperature time series from 5395 stations across Europe provided by ECA&D (Klein Tank et al. 2002) and then applied to minimum temperature expected for 2041–2070. Future temperature values were averaged from those predicted by five global climate models (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESMAP1-2-HR, MRI-ESM2-0, and UKESMAP1-0-LL) under CMIP6 scenario SSP-370, using datasets provided by CHELSA (MAP09). The result was mapped in MAP13.

All variables were rescaled to a range [0, 1]. Priority P was calculated by assigning equal weight to temperature and air quality, and multiplying the result by d by applying Equation (3).

$$P = d\left(\mathrm{NTN} + \frac{a1 + a2 + a3}{3} \right) \quad (3)$$

This is consistent with a risk assessment framework (risk = hazard × vulnerability). The result was mapped in PMAP2.

Climate Mitigation

We assessed potential carbon stock increases after afforestation using IPCC methodologies (2006), relying on Tier 2 and Tier 3 data to account for the heterogeneity of soil properties and drivers.

First, we estimated the carbon stock in non-forest soils under their current land uses, by assigning a value for soil (SC_0) and biomass (BC_0) carbon from the IPCC database (IPCC 2019) to each unique combination (Table S2) of land use (MAP02), climate zone, and soil type (MAP10). Climate zones map (MAP14) at 1 km resolution was created based on the IPCC classification (IPCC 2019) using climatic data from the CHELSA dataset (MAP09). We associated each land use category in the CLC dataset with the most similar one in the IPCC database.

Second, we calculated potential soil (SC_p) and biomass (BC_p) carbon stock attained post-afforestation. We derived SC_p (Table S2) as above, assuming "Forest" as land use. We assigned BC_p (Table S3) corresponding to the natural potential vegetation type (MAP05), using the mean above- and below-ground values reported by the National Forest Inventory (Gasparini et al. 2022). Crucially, the use of mean values ensures that forests at all stages of development are captured, not just fully mature stands. Because of this, our results are not linked to a specific time horizon; rather, they represent the carbon pool expected when a forest has reached the current average conditions of Italian forests.

We calculated carbon gain or losses (ΔC) following afforestation subtracting from the potential carbon stock after afforestation the current carbon stock as follows:

$$\Delta C = (\mathrm{SC_p} + \mathrm{BC_p}) - (\mathrm{SC_0} + \mathrm{BC_0}) \quad (4)$$

Negative values, indicating potential carbon losses from afforestation, were set to 0. The results were mapped in PMAP3.

Water Regulation

To detect the priority areas where tree planting can improve the water storage, we applied one of the most popular hydrological methods, the curve number (CN) methodology (Ponce & Hawkins 1996). This hydrological parameter serves as a fundamental empirical approach to estimate the surface run-off, considering both the soil properties and the land cover characteristics. CN is widely used; therefore, for determining the spatial distribution of run-off generation (Mockus 1964). The CN values range from 0 to 100.

We compiled different spatial datasets, including CLC (MAP02), hydrologic soil group (HSG, MAP11), and the DEM (MAP03). First, we assigned an initial CN value (CN_{raw}) combining land cover category and HSG (Table S4; Cislaghi et al. 2024). Second, we employed a slope-adjusted formulations of CN_{raw} to include the terrain steepness variability (Wu et al. 2024) as follows:

$$\mathrm{CN_{adj}} = \mathrm{CN_{raw}} \times \frac{322.79 + 15.63\alpha}{\alpha + 323.52} \quad (5)$$

where α is the slope (in mm^{-1}), considered valid within the range [0.14–1.4]. Values outside this range were assigned the corresponding boundary values. CN_{adj} was mapped in MAP15 (Fig. S5).

Then, we calculated the current potential soil water retention S_0 (Mishra & Singh 2003; Mishra et al. 2014) using the standard formula:

$$S_0 = \frac{25400}{\mathrm{CN_{adj}}} - 254 \quad (6)$$

where S_0 is expressed in mm. Afforestation impact was calculated by assuming that all the land cover converts to a healthy forest, with CN in function of the HSG (Table S4). We repeated the procedure (Eqs. 5 & 6) providing the future potential soil water retention S_p. Then, we computed the difference ΔS between S_p and S_0 representing the hydrological improvements (more water yield and less surface run-off). The final gridded map of ΔS was normalized and the results generate PMAP4.

Combining Priority Maps

We overlaid the four individual PMAPs (PMAP1, PMAP2, PMAP3, and PMAP4) to generate two synthetic maps, representing priority areas from a multifunctional perspective. Since

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the score distributions for the four afforestation goals are markedly different, due to the specific methodologies applied for each objective, the use of absolute mean scores would be misleading. Therefore, we considered the average of the corresponding percentile classes (PMAP5). In the second map (PMAP6), we visualized the number of goals (0–4) under which each pixel is classified as an HPA. This highlights areas where afforestation can simultaneously maximize benefits for multiple ESs.

Results

About 55% of the Italian territory has been found to be potentially suitable for afforestation (Fig. 2A). A large part of the area (84%) is currently occupied by agricultural land, and a very small proportion is covered by urbanized zones (9%). Sicily exhibits the largest relative suitable area for afforestation, accounting for 6% of the national territory, followed by Emilia-Romagna and Sardinia, each with 5% (Fig. 2B).

The *F* coefficient (MAP12; Fig. S2) ranges from 0 to 64,198, although more than 88% of the assessed areas fall below a value of 10,000. Its distribution mirrors in the score indicating afforestation priority (Fig. 3B), which shows a pronounced skewness with values heavily concentrated near zero. Since *F* is the main driver in the model, MAP12 closely resembles the priority afforestation map (PMAP1, Fig. 3A). However, the inclusion of the two additional factors, PA and PW, introduces local-scale variations (e.g. Fig. 3C).

Priorities for afforestation aimed at enhancing ecological connectivity (Fig. 3A) are mainly concentrated in the major lowlands: the Po Valley (extending from Piedmont to Veneto), and the Apulian plains (with 20 and 18% of the HPAs, respectively; Table S5). Other notable concentrations are found along the Adriatic coast (west coast) and in peri-urban areas surrounding the metropolitan cities of Turin, Rome, Naples, and Catania. Specifically, HPAs correspond to areas with a score above 0.09 (Fig. 3B). Sardinia, generally characterized by lower *F*, exhibits the lowest priority for such interventions (48% of suitable areas has a score of 0).

Population density shows a wide but skewed distribution toward zero, with vast sparsely populated areas and a few urban centers, such as Rome, Naples, Milan, and Turin, with densities that exceed 30,000 inhabitants per km^2. This pattern strongly influences the final score: HPAs include areas with a score above 0.03 (Fig. 4B). The PMAP aimed at human health (PMAP2; Fig. 4A) shows a significant overlap with the most urbanized zones, notably the Po Valley, characterized by both high levels of atmospheric pollution and high population density. Areas bordering the main industrial centers such as Milan, Venice-Treviso-Padua, and Turin stand out with high priority (e.g. Fig. 4C). Similarly, high priority is found in correspondence with major cities such as Rome, Naples, and Florence. The NTN projected for the future (MAP13; Fig. S3) raises priorities along densely populated coastal zones, notably the Adriatic coast. Sparsely populated areas are characterized by very low priority, as only a small portion of the population would benefit from the public health-related ESs resulting from new forests. This is evident in the regional distribution (Table S5), with Lombardy and Veneto showing large shares of HPAs (18 and 15% of HPAs, respectively), while Sicily and Sardinia, with vast low-population density zones, have large shares of low-priority zones.

The climate zone map (MAP14; Fig. S4) developed for this study provided a suitable spatial resolution for the analysis.

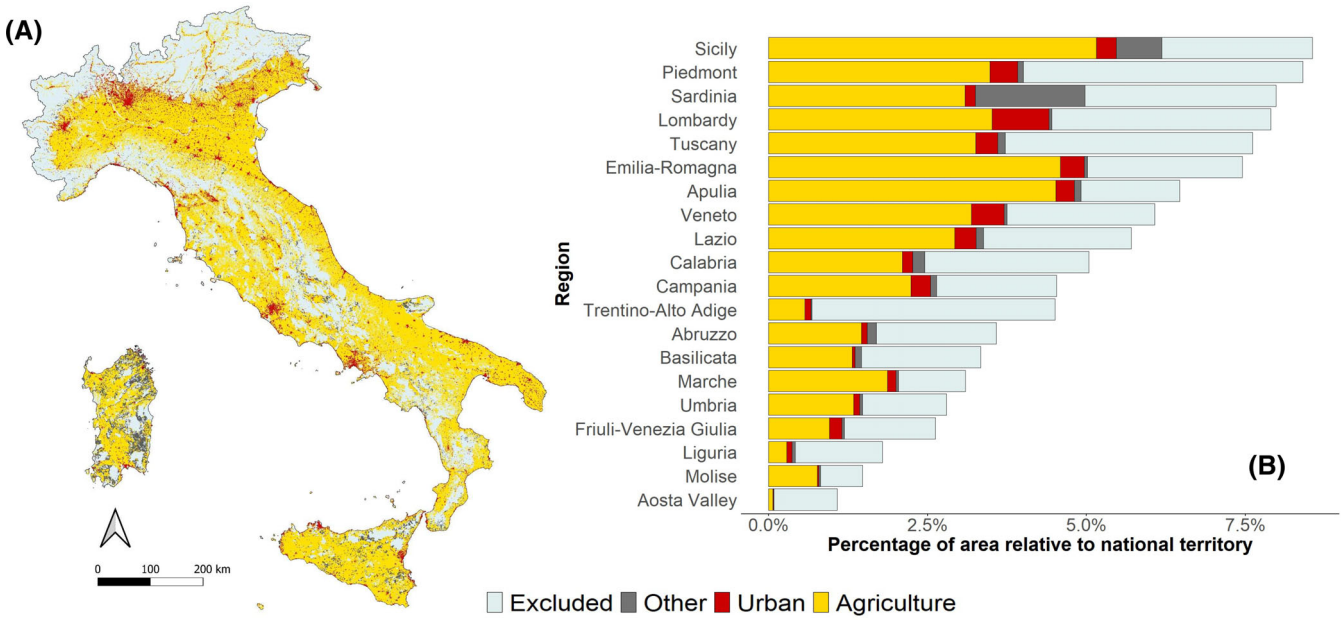

Figure 2. (A) The map visualizes the areas identified as suitable for afforestation. (B) The bar chart details each region's percentage of surface area relative to the national total. Colors indicate land use categories derived from the CLC dataset (MAP02): urban areas (artificial surfaces), agricultural areas, other land use, and areas excluded from afforestation.

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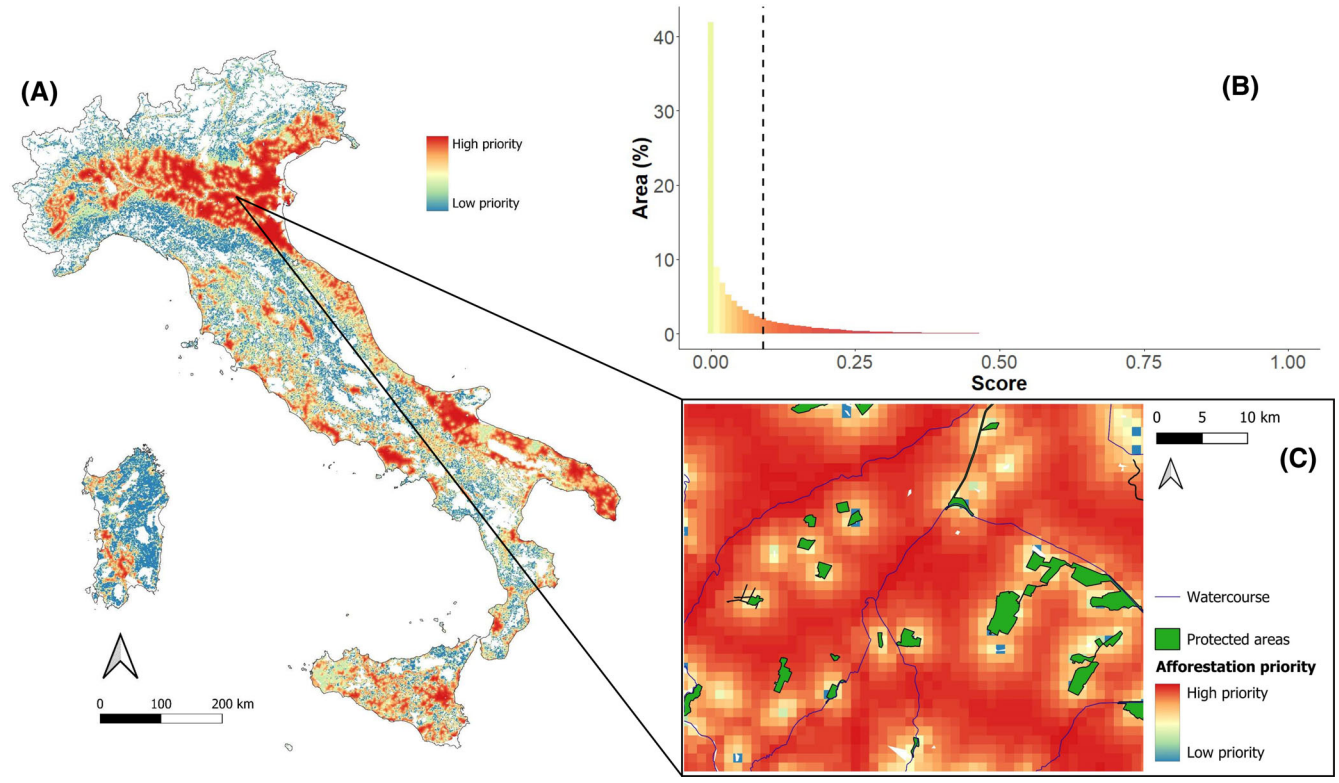

Figure 3. (A) The map PMAP1 illustrates the spatial distribution of afforestation priority, specifically for the ecological connectivity goal. (B) Histogram showing the distribution of afforestation scores across the areas considered; the black dashed line indicates the 80th percentile threshold. (C) Zoomed-in view illustrating an example how afforestation priority varies within a highly fragmented landscape that includes rivers and protected areas.

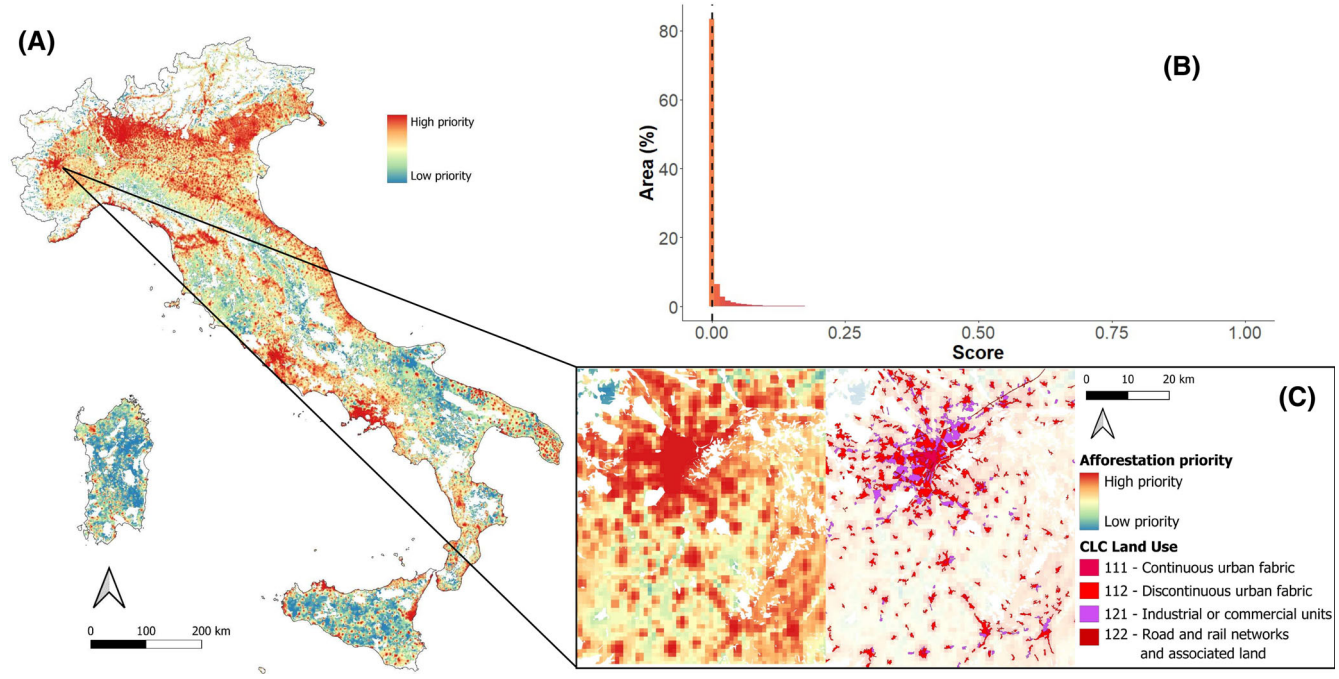

Figure 4. (A) The map illustrates the spatial distribution of afforestation priority, specifically for the human health goal. (B) Histogram showing the distribution of afforestation scores across the areas considered; the black dashed line indicates the 80th percentile threshold. (C) Zoomed-in view illustrating an example how afforestation priority is strongly associated with urban land use.

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Carbon-related goals reveal a stark dichotomy between lowland areas, characterized by low priority, and mountainous zones, which instead exhibit high priority (PMAP3; Fig. 5A). This spatial distribution exhibits a strong correlation with climate. Those areas with a significant ΔC are located in climatic zones classified by the IPCC as Warm and Cool Temperate Moist (e.g. Fig. 5C). Soil type in Italy does not vary significantly, as 95% of the national territory is classified as High Activity Clay Soils; therefore, this variable has a limited influence on the overall results. Notably, zero carbon gains or losses were observed in rice paddies (e.g. Fig. 5C), which currently store large quantities of soil carbon thanks to the temporary waterlogging. Some orchard areas also exhibited negative ΔC. This outcome is explained by the fact that, based on the available data, the existing biomass in these areas exceeds that of the potential natural vegetation (Table S3). While the highest prioritization scores are concentrated along the Alpine and Apennine mountains, Sicily stands out as the region encompassing the largest extent of HPAs (more than 18% of the national total). In this case, HPAs are the areas with a score above 0.28 (Fig. 5B).

The highest priorities for afforestation aimed at water regulation (Fig. 6A) are concentrated in vineyard areas as well as in heavily urbanized areas (e.g. Fig. 6C), particularly around Milan, Florence, Rome, and Naples. In these areas, ΔS values generally range between 35 and 65 mm. The regions that would benefit most from afforestation targeting the water regulation are those lying in the Po Valley, such as Lombardy and Veneto (16 and 14% of HPAs, respectively). HPAs for water regulation are areas with a score above 0.27. Low priority was found in mountainous areas, where steeper slopes translate to modest potential gains in soil water infiltration.

From the analysis of the composite maps, we observed that higher average priority was concentrated at densely urbanized areas (PMAP5; Fig. 7A). This is further confirmed in PMAP6 (Fig. 7B): only 13% of the total suitable area exhibits high priority for at least two of the objectives considered here, and this happened predominantly around the most urbanized contexts. This also highlighted the existence of significant trade-offs when trying to establish priority locations for afforestation aimed at different goals.

Discussion

The flexible approach to each goal proved effective in identifying priority areas for ESs improvement. Its strength lies in accounting for diverse factors and assessment criteria. Notably, the identification of priority areas and maximum benefits followed different logics: for ecological connectivity and human health, priorities corresponded to areas with the most severe issues; conversely, for water regulation and climate mitigation, priorities aligned with areas showing the greatest projected improvement under future forest cover.

It is crucial to consider that the areas identified as suitable for afforestation are not entirely convertible to forest. In urban areas, for instance, usable patches may be small, below the analysis resolution, yet significant for achieving specific ESs objectives. The prevalence of agricultural areas (84%) highlights the need to adopt agroforestry approaches or careful land use

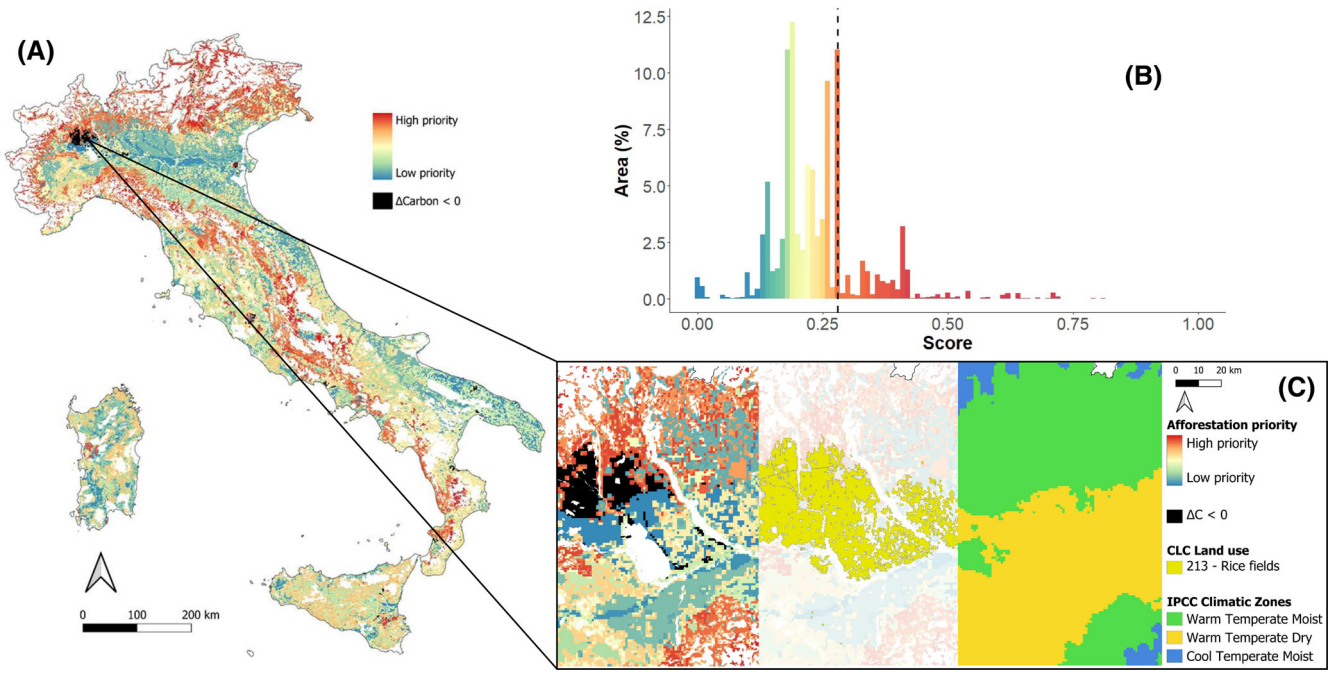

Figure 5. (A) The map illustrates the spatial distribution of afforestation priority, specifically for the climate mitigation goal. (B) Histogram showing the distribution of afforestation scores across the areas considered; the black dashed line indicates the 80th percentile threshold. (C) Zoom-view showing both lack of priority in rice field areas, and the correlation between HPAs spatial distribution and climatic zones.

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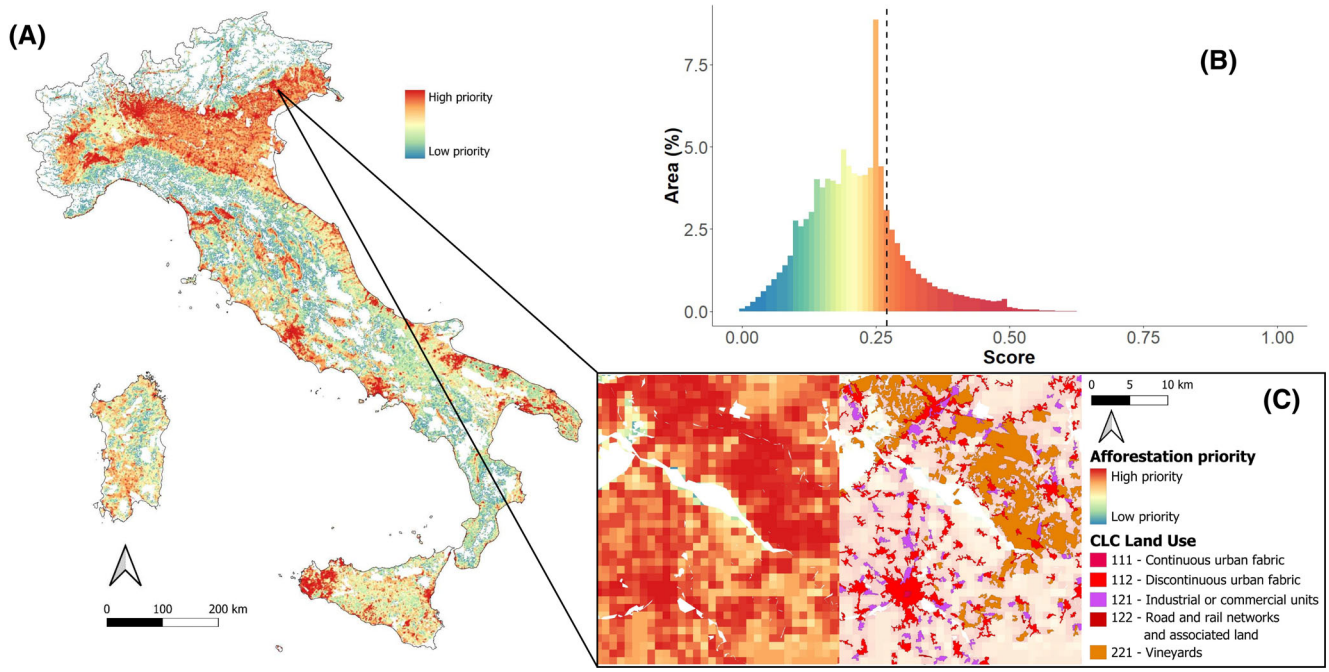

Figure 6. (A) The map illustrates the spatial distribution of afforestation priority, specifically for the water regulation goal. (B) Histogram shows the distribution of afforestation scores across the areas considered; the black dashed line indicates the 80th percentile threshold. (C) Zoomed-in view highlighting the relevance of vineyards and urban areas in the spatial distribution of afforestation priority.

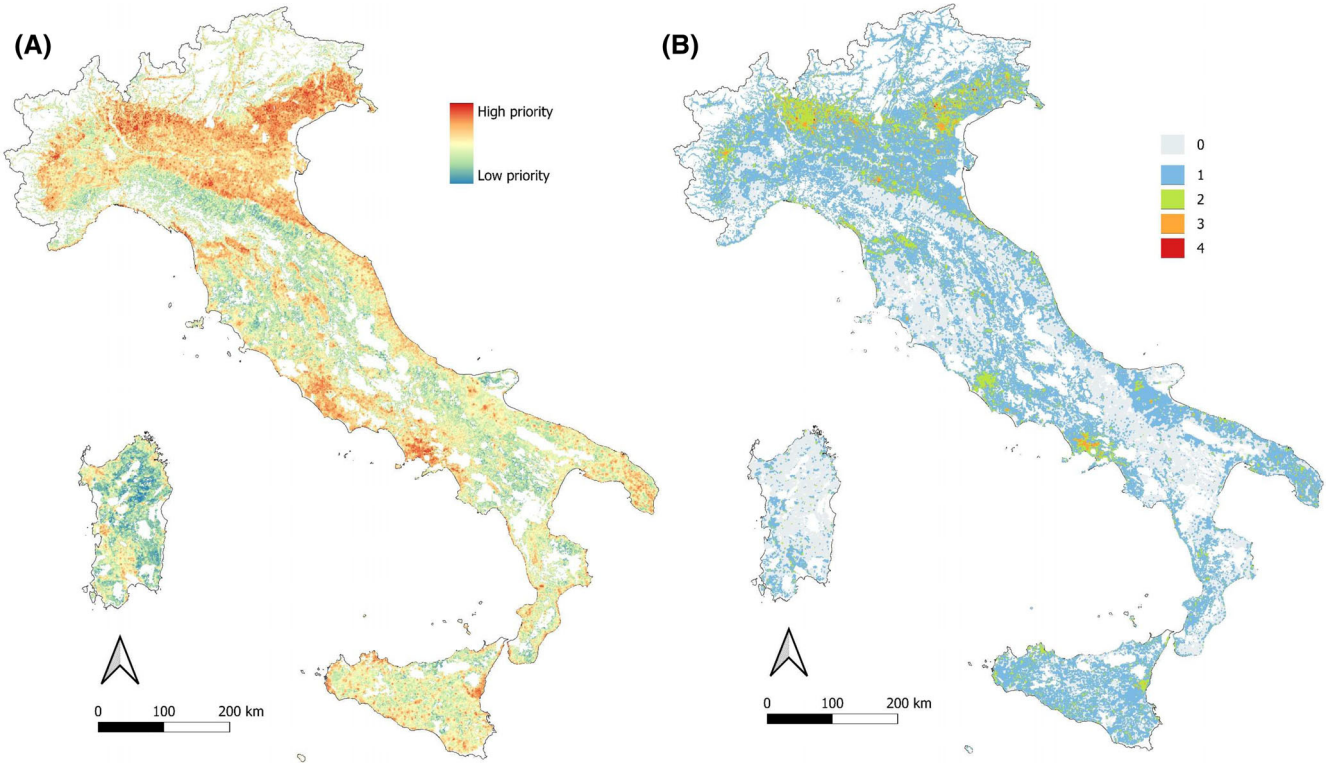

Figure 7. (A) The displays the average afforestation priority, calculated by averaging the percentile ranks of the scores obtained for each of the four afforestation goals, and highlights areas with higher overall priority. (B) The map indicates the number of objectives (out of four) for which each point is considered HPA. Both maps reveal a predominant concentration of higher priority areas within densely urbanized contexts.

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planning that integrates increased tree cover with sustainable agricultural practices. This study provides a national-level overview, offering a basis for more detailed analyses at the local scale, focused on actually available areas.

High values of F observed in lowland and coastal zones, driven by intensive agriculture and extensive urbanization, makes them priority zones for interventions aimed at enhancing ecological connectivity. This aligns with global trends where urban expansion leads to significant habitat loss and fragmentation, negatively impacting biodiversity by reducing species richness, altering community composition, and disrupting ecological processes (McKinney 2006; McDonald et al. 2008). Recognizing the crucial role of urban environments for biodiversity conservation (Dearborn & Kark 2010), investing resources in these areas is essential. Specifically, urban forests can exhibit high biological richness (Alvey 2006) and serve as ecological corridors or stepping stones (Lapin et al. 2024). Similarly, the conversion from conventional agriculture to agroforestry or the introduction of ecological infrastructure (e.g. hedgerows and riparian buffers) promotes an increase in biodiversity, by creating diverse microhabitats (Santos et al. 2022). Careful planning can maximize connectivity between protected areas, a crucial strategy for effective population conservation (Coetzee et al. 2014). However, in planning afforestation interventions, it is vital to safeguard specific priority habitats, such as open grasslands and clearings. In Italy, these habitats are particularly vulnerable due to forest expansion and the abandonment of traditional land management practices (Pallotta et al. 2022). Therefore, a balanced approach is essential to avoid inadvertently reducing biodiversity by converting valuable open habitats.

As suggested by the resulting map and given the high percentage of the Italian population residing in urban areas, urban forests play a crucial role for public health and quality of life in the cities. This focus is globally pertinent, as the share of the world's population living in urban areas is projected to rise from 55% in 2019 to 68% by 2050 (UN 2019). The urban areas identified as suitable in this study are not entirely afforestable, and the actual available surface will be smaller. It is therefore essential to rethink and redesign green infrastructures to maximize their ecological functionality and social accessibility within the existing urban fabric. Urban areas present both constraints, such as historic or densely built neighborhoods, and opportunities, like former industrial sites, which can be repurposed for urban greening (Rink & Schmidt 2021). Including urban areas in our methodology departs from many approaches and underscores the need for context-specific priorities balancing ecological, social, and cultural considerations (Resemini et al. 2025).

The results for climate mitigation differ from others, suggesting that afforestation strategies specifically oriented toward climate mitigation may require a distinct spatial approach. ΔC was higher in the Warm and Cool Temperate Moist regions, where wet climatic conditions and higher precipitation enhance soil carbon storage (Ogle et al. 2005) through decreased decomposition rates (Schuur et al. 2001), increased mineral-associated organic matter (Heckman et al. 2023) and hydroclimatic influence (Huang et al. 2023). This underscores water availability as a key driver for forests in the Mediterranean area. Under comparable conditions of soil and land use, climate will play a decisive role in shaping additional carbon storage. Also urban areas present a high potential carbon storage (Teo et al. 2021), although our methodology might not be refined enough to properly capture it. Conversely, results showed a low or negative ΔC in rice paddies, consistent with existing literature (Schwarz et al. 2024).

Regarding water infiltration potential, low values of the S index, associated with high values of CN, are found in urbanized areas, characterized by a high percentage of impervious surfaces. The conversion of impervious surfaces into forests leads to the most significant increases in water infiltration into the soil. This practice aligns with the "sponge city" concept and falls within Nature-Based Solutions for sustainable urban drainage, representing a strategic approach to mitigate frequent flooding and water management issues in urban areas. Among agricultural areas, cultivating crops in straight rows without interrow grass cover causes significant run-off generation and low capacity of water storage. Most vineyards show these features, exacerbated by frequent management practices that cause soil compaction. In these areas, agroforestry techniques can be implemented to improve hydrological functions through enhanced soil water retention and microclimate regulation (Favor & Udawatta 2021). This is particularly important under climate change, highlighting agroforestry as a multifunctional ES provider, also supporting agricultural productivity.

Consistent with earlier findings that highlight the inherent trade-offs among ESs (Chisholm 2010; Doelman et al. 2020), the limited spatial overlap of HPAs across multiple goals suggests that afforestation projects should focus on one or two key objectives rather than aiming to maximize all benefits simultaneously. The concentration of multifunctional priorities in densely populated areas underscores the strategic value of urban and forests in enhancing environmental quality, biodiversity, and well-being. This reinforces the importance of integrating multifunctional green infrastructure into urban planning.

The PMAPs can be used in several ways: (1) observing the maps individually, to align projects with specific goals by targeting priority areas at national scale; (2) to evaluate whether preselected sites, due to land tenure or availability, are relevant for any ESs and tailor interventions accordingly; (3) to visualize overlapping HPAs and plan for multifunctionality.

Given Italy's ambitious goal of planting 6.6 million trees by 2026, our study provides a spatially explicit information framework at national scale, identifying priority areas for reforestation based on multiple ESs objectives. The resulting maps can therefore represent a fundamental decision-support tool to direct planting efforts toward areas where the investment will generate the greatest environmental and social benefits. The spatial differentiation of priorities highlighted by our analysis underscores the need for a strategic and targeted approach to achieve the national goal, optimizing resources and maximizing afforestation impact.

This study could be enhanced by incorporating additional ESs as explicit targets, such as provisioning or cultural services (Burke et al. 2023), and by developing specific methodologies for each. Moreover, future work could integrate species-

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selection models to evaluate how different tree species or planting designs influence ES provision, thereby supporting more realistic and operational planning (Lautenbach et al. 2017; Baggio-Compagnucci et al. 2022).

The 1 km resolution is appropriate for strategic national planning and can also be relevant at macro-regional or regional scales. However, finer-scale local analyses remain advisable for operational planning, stakeholder engagement, and integration into local development policies. This enables translating national strategies into actionable, context-specific interventions.

An important aspect to consider is the temporal evolution of territorial conditions (Łągiewska & Bartold 2025) and, consequently, the need to regularly update the results in line with newly released datasets. For example, the outcomes of this study could be updated when the new CLC 2024 dataset becomes available (Copernicus n.d.). Another promising direction concerns the emerging availability of do-it-yourself tools and automated platforms able to update land cover information and detect changes over user-defined time ranges (Bartold et al. 2025). Such systems, based on automated satellite-image processing, provide an opportunity to complement traditional maps. Incorporating these approaches could enhance the transferability of our methodology, enabling more frequent updates and supporting dynamic applications and territorial management.

The visualization of priority in percentiles significantly aids administrative and policy decisions by providing a relative ranking of suitability. This approach allows to set pragmatic targets (e.g. top 10 or 20%) aligned with available funding and facilitating more efficient resource allocation. Furthermore, the distribution analysis of HPAs in the regions is instrumental for national planning. It provides a strategic overview, enabling authorities to understand the spatial distribution of diverse afforestation opportunities across the country. This macroscopic perspective is crucial for designing a comprehensive, nation-wide afforestation program that effectively distributes efforts and maximizes benefits by tailoring interventions to regional characteristics and needs. National scale results should inform regional forest programs, which translate national strategies into regional priorities and guide both strategic and operational decisions at municipal level. Such multi-level integration enhances coherence between national goals and local actions, boosting the impact and feasibility of afforestation.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Degree of ecological resistance ("cost") to animal movement played by the land uses.
Table S2. Values for current soil (SC_0) and biomass (BC_0) carbon stock, and potential soil carbon stock post-afforestation (SC_p).
Table S3. Values for potential biomass carbon stock post-afforestation (BC_p) corresponding to the natural potential vegetation type.
Table S4. Values of CN parameter values in function of land use (Corine Land Cover 2018) and hydrologic soil group (A–D).
Table S5. Percentage of high-priority areas (HPAs) per region relative to the total HPAs.
Figure S1. Overview of the factors considered in each goal-specific methodology.
Figure S2. MAP12—fragmentation (F) map, colored by quantiles.
Figure S3. MAP13—map of number of tropical nights (NTN) per year in future climate scenarios (period 2041–2070), colored by quantiles.
Figure S4. MAP14—IPCC climatic zones map.
Figure S5. MAP15—map of CN_{adj} (slope-adjusted values of CN), colored by quantiles.

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