Forest Ecology and Management 602 (2026) 123387

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Active and passive forest management: Effects on ecosystem services across protected and unprotected areas in a Southern European regional context

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A R T I C L E I N F O

Keywords:
Unmanaged forests
Rewilding
Forest land abandonment
Latent reserves

A B S T R A C T

Landscape-scale forest management is widely recognized as a means to sustain and enhance multiple forest ecosystem services. Recent policy frameworks, such as the EU2030 Forest and Biodiversity Strategies, and approaches including sustainable forest management, closer-to-nature silviculture and rewilding, point towards contrasting management pathways: some encourage active interventions through silvicultural practices, whereas others promote strict non-intervention. Yet the spatial distribution of these different approaches at the regional level and their potential to provide ecosystem services remain poorly understood. In this study, we investigated how diverging management approaches influence ecosystem services across the entire forested area of the Piedmont region (Italy). Based on data from regional forest management plans, we reclassified intended management strategies into Active forest management (including silvicultural practices of varying intensity) and Passive forest management (no intervention), and quantified the distribution of both management types. Using principal component analysis (PCA) and generalised linear models (GLM), we explored relationships between management type and three ecosystem services: carbon stock, fire hazard mitigation, and biodiversity (diversity of tree species). We also examined how Protected Areas are associated with the different types of management and whether they can mediate their effect on ecosystem services. Our results show that 60 % of Piedmont's forests are planned for Active management, though implementation is hindered by increasing forest land abandonment. Active forest management was associated with higher levels of the three ecosystem services. Protected Areas seem to promote Passive management, while their influence in ecosystem services provision appears scarcely significant. Based on our findings, we advocate: (i) promoting active forest management in abandoned forests, (ii) prioritizing active management approaches to enhance ecosystem services provision, and (iii) leverage unprotected passively managed forests when expanding the Protected Area network, a priority set out in the EU2030 Forest and Biodiversity Strategies.

1. Introduction

Forests provide essential ecosystem services that are crucial for the promotion of sustainable development and environmental protection worldwide (Brockerhoff et al., 2017; Cavalli et al., 2022; Scherpenhuijzen et al., 2025; The UN 2030 Agenda for Sustainable Development, 2015). These services include the provision of wood and non-wood forest products, the regulation of biogeochemical and hydrological cycles, the mitigation of natural hazards, and the support to habitat and biodiversity conservation (Millennium Ecosystem

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https://doi.org/10.1016/j.foreco.2025.123387
Received 23 September 2025; Received in revised form 23 November 2025; Accepted 25 November 2025
Available online 5 December 2025

Assessment, 2005; Spadoni et al., 2020; Winkel et al., 2022).

In contemporary Europe, the most widely recognized strategy to optimize ecosystem services, while considering defined priorities and potential trade-offs, is the adoption of different forest management approaches through forest land planning (Brockerhoff et al., 2017; Gregor et al., 2024; Van Der Plas et al., 2018). Historically, forest management aimed almost exclusively at wood supply and was typically implemented at the level of single properties (McGrath et al., 2015; Rupf, 1960). Currently, effective forest management requires planning at landscape and regional scales to ensure the provision of a wide range of ecosystem services, to meet societal demands for timber and other raw materials, while maintaining ecological processes, reducing natural hazards, and supporting other services (Gregor et al., 2024; Larsen et al., 2022; Van Der Plas et al., 2018; Winkel et al., 2022). Consequently, various forest management approaches are now employed across Europe with the aim to supply one or multiple ecosystem services, ranging from extensive low-intensity practices to restore natural ecological dynamics, to intensive short-rotation monocultures focused on biomass production for energy (Betts et al., 2021; Forest Europe, 2015; Van Der Plas et al., 2018; Wang et al., 2025).

Forest management approaches can be broadly classified into the two main categories of active and passive management for ecosystem services provision (Bolte et al., 2009; Carey, 2006). The first promotes targeted interventions of different intensity to regulate forest structure and functions (Bennett et al., 2024). Conversely, the second involves no human intervention, aiming to leave forests to their natural dynamics (Duncker et al., 2012; Kulakowski et al., 2017). Active or passive approaches may lead to markedly different outcomes, also depending on the specific social-ecological context (Bennett et al., 2024; Kulakowski et al., 2017). However, many European regions lack spatially explicit information on the distribution of these two management types. In addition, the actual influence of both approaches on the provision of ecosystem services remains largely unclear.

These knowledge gaps are critical in light of recently proposed strategies for natural resources management. For instance, the *proforestation* approach advocates for allowing forests to reach their full ecological potential without silvicultural interventions, such as coppicing, thinning, or variable retention harvest (Moomaw et al., 2019). Proforestation can be included into the broader concept of *rewilding* (Jørgensen, 2015; Perino et al., 2019), which promotes forms of passive management. Furthermore, the decline in anthropogenic activities of the primary sector in rural and mountainous areas frequently leads to the abandonment of silvicultural practices in previously actively managed forests (i.e., forest land abandonment; FAO, 2006; Romero-Díaz et al., 2024). In such areas and after extended periods of under-utilization passive management approaches tend to be preferred in subsequent forest land planning (Navarro and Pereira, 2012). On the other hand, approaches such as *sustainable forest management* (Siry et al., 2005) or *closer-to-nature forestry* (Larsen et al., 2022) support management approaches involving varying degrees of active intervention (Scherpenhuijzen et al., 2025; Wang et al., 2025).

Advancing knowledge of these issues is critical for informing and enhancing the effective implementation of environmental policies, such as the European Biodiversity and Forest Strategies for 2030. One of the key objectives of both strategies is to increase the EU's land protected area coverage from 26.1 % (as of 2022) to 30 %, with one-third of these areas designated under strict protection (European Commission, 2020). In fact, the extent to which Protected Areas (PAs) are associated with active or passive forest management is generally unknown (Oldekop et al., 2016). On one hand, PAs may facilitate funding for forest interventions, such as targeted measures under the European Rural Development Fund measures, or through streamlined procedures for obtaining sustainable forest management certifications. On the other hand, PAs might introduce restrictions on forest land use, particularly within zones under strict protection (Ameztegui et al., 2021; Oldekop et al., 2016). In some cases, these restrictions might even boost the process of forest land abandonment, further reinforcing the long-term shift towards passive management (Oldekop et al., 2016). In addition, it remains unclear whether Protected Areas mediate the relationships between active and passive forest management and the ecosystem services they currently provide (Hayes, 2006).

A thorough assessment of current forest management types associated with PAs, and of their corresponding levels of ecosystem services provision, could offer essential insights to support a targeted implementation of new Protected Areas to meet the objectives of the EU strategies while accounting for trade-offs between environmental conservation and local communities' livelihood (Hirschnitz-Garbers and Stoll-Kleemann, 2011; Oldekop et al., 2016). Evaluating the existing forest management mosaic could help identify areas assigned to passive forms of management that lie outside PAs. Accordingly, assuming that areas under passive management do not constitute a critical economic resource for extractive purposes to local communities, yet hold considerable ecological value, these may be considered as 'latent reserves' (Portier et al., 2021) suitable for designation as new Protected Areas (Mouillot et al., 2024). With the term latent reserve, we refer to the definition introduced by Portier et al. (2021), referring to "forest stands that, among other criteria, have been free of human influence for at least 40 years". However, we further refined this definition by limiting it to forests located outside Protected Areas where silvicultural interventions are neither planned nor required for the provision of target ecosystem services, and which are therefore left to natural dynamics for the duration of validity of a forest plan or longer.

Given this context, this study addressed the following research questions within the frame of regional-level dynamics in forest ecosystems of southern Europe:

a. What is the distribution of forest land designated to be actively and passively managed within a Southern European regional context?
b. What are the current levels of ecosystem services provision associated with active and passive forest management?
c. To what extent are Protected Areas associated with the two different types of management? Does their presence influence the provision of ecosystem services associated with active and passive forest management?

To address these research questions, we focused on the Italian region of Piedmont. This region offers a complex mosaic of forest management types across approximately one million hectares of forest landscape, ranging from remote high-altitude forests to intensive monospecific plantations. In addition, Italy is still below the EU2030 target of 30 % of its land under Protected Area (21,4 % of the national surface is under Protected Areas; Eurostat, 2022) and Piedmont's forests could offer space for the designation of new Protected Areas. Several hypotheses listed in Table 1 were derived from the aforementioned research questions to be tested through our analyses. We used regional forest planning documentation to classify the forest territory into the two main different types of forest management, i.e., active versus passive. To assess the provision of ecosystem services, we selected three: fire hazard mitigation, carbon stock, and tree species diversity as a proxy for forest biodiversity. For each service, we developed a Generalised Linear Model (GLM), with management type as the main treatment factor and Protected Areas as an interaction term. To characterize the different forest management classes, we also included a set of topographical, accessibility, and climate variables, and applied a Principal Component Analysis (PCA) to describe this multivariate system.

2. Materials and methods

2.1. Study area

The study area encompasses the Italian region of Piedmont (Fig. 1), located in the North-West of the country, bordering France and

Table 1
Research hypotheses related to the Piedmont region.

Research Questions	Hypotheses	Main reference (s)	Methodology
a. What is the distribution of forest land designated to be actively and passively managed within a Southern European regional context?	Most of Piedmont forest land is passively managed	Gottero et al. (2007)	Geospatial analyses
b. What are the current levels of ecosystem services provision associated with active and passive forest management?	Active management is associated with higher values of ESs	Brockerhoff et al. (2017); Gregor et al. (2024); Spadoni et al. (2023)	Principal Component Analysis (PCA); Generalised Linear Models (GLMs)
c. To what extent are Protected Areas associated with the two different types of management? Does their presence influence the provision of ecosystem services associated with active and passive forest management?	(i) Protected Areas are predominantly associated with passive forest management (ii) PAs tend to decrease ESs provision values in actively managed forests, while they increase it in passively managed forests	(i) Ameztegui et al. (2021); Guadilla-Saez et al. (2020); Oldekop et al. (2016) (ii) Guadilla-Saez et al. (2020); Santoro and Piras (2023)	Geospatial analyses; Principal Component Analysis (PCA); Generalised Linear Models (GLMs)

Switzerland. It extends for approximately 2.5 million hectares, of which around one million (38 % of the total area) is covered by forests, distributed across 21 forest types. The region spans a broad elevation gradient (from 35 to 4634 m a.s.l.) and features diverse landscapes, from plains to hills and mountains, shaping both climate conditions and vegetation. According to the Köppen–Geiger classification, it is mainly warm temperate, with boreal conditions in parts of the alpine belt and alpine tundra at the highest peaks (Rubel et al., 2017). Forest cover ranges from about 10 % in the plains, dominated by oak stands, to approximately 40 % in the hills, with a predominance of chestnut and black locust formations, and around 57 % in mountains, where beech and larch prevail (Camerano et al., 2008). This region has 170 inhabitants per square kilometre as of 2020, and most of its forest land has been actively managed through the centuries (Bruzzese et al., 2020; Gottero et al., 2007). Nonetheless, since the sixties and seventies of the last century the region has experienced progressive forest land abandonment. Piedmont includes a wide network of Protected Areas and Nature 2000 sites, including some of the first Italian national parks. As of 2023, Protected Areas cover 18.2 % of the total regional landscape and 18.5 % of the forest land (IPLA, 2023).

2.2. Data

2.2.1. Forest management

We used forest regional plans to identify intended forest management approaches. Specifically, we used information from the 2016 Piedmont's Regional Forest Map (*Carta Forestale Regionale*), which includes 92,083 polygons (i.e., 'Forest Polygons') covering all forested areas (public and private) of the region (932,495 ha). While the forest cover and the polygons' geometry are updated to 2016, the associated management data is based on the Regional Forest Territory Plans (*Piani Forestali Territoriali*, PFTs) from the year 2000. Each forest polygon includes information on planned interventions, established in the year 2000 to assign a potential, though not mandatory, management objective to each forest stand, with a validity of 30 years. Planned interventions were partly established based on past management activities, so that stands designated for active management have been likely actively managed in the past, while those designated for passive management may have been passively managed or unmanaged in the previous decades. Accordingly, unmanaged forests prior to the implementation of PFTs in 2000 include areas abandoned for an extended period (i.e., several decades), and sparsely present hardly accessible forests that may have never been managed in the past. Such areas were not excluded from planning within PFTs but were designated to passive management assuming that this approach could better enhance their provision of given ecosystem services. PFTs were innovative at the time of their introduction, and remain so, as they cover the entire forest land in the region of Piedmont and are implemented through larger forest polygons defined by topographical and ecological features (e.g., watersheds, exposition, tree species composition, etc.) rather than based on individual cadastral parcels. This allows for the consideration of ecological processes extending beyond jurisdictional borders to grant the provision of ecosystem services other than wood production for individual landowners. In contrast, in many other European regions, including parts of Italy and Piedmont before 2000, forest planning is still limited to smaller areas constrained by cadastral property boundaries, with a predominant focus on extractive purposes (Tereşneu et al., 2016; Weir, 1997).

We reviewed planned forest interventions from PFTs and classified them as Active Forest Management (AFM) and Passive Forest Management (PFM) for ecosystem services provision. PFM included approaches aimed at leaving forests to dynamics not directly influenced by human intervention, while AFM was associated with approaches involving purposeful human interventions affecting the structure and the dynamics of forest stands. According to PFTs' nomenclature, management types of *natural evolution, free evolution, and controlled evolution* were associated with PFM. Conversely, AFM included the management types called *coppicing, active conversion, silvicultural treatments, thinning, thinning and conversion, coppice-with-standards management, mixed silvicultural system, forest restoration, sanitary cutting or enrichment planting, adapted successive cuts, patch cutting, strip cutting, slit cutting, selection cutting, and conversion.* Other details about the management approaches and their reclassification are provided in section SM1 of the Supplementary Materials.

Planned interventions from PFTs were used as proxies of different forest management types (AFM and PFM) implemented across the regional forest landscape. Because the nature of the plans was not mandatory, there may be a mismatch between planned and implemented management activities. Some stands destined to passive management might have been actively managed. Conversely, the withdrawal of active forest management activities in stands designated to active management – where the designation was likely indicative of a prior history of active management, as stated above – was intended as forest land abandonment (Fig. 2). However, it was not possible to assess forest land abandonment within this study. To verify if proposed management objectives from PFTs have been realised, we compared them with data from the Regional Forest Unit Management Plans (*Piani Forestali Aziendali*, PFAs) promoted by forest owners and approved between 2016 and 2022 with a validity of 10–15 years. Although PFAs cover a much smaller forest area, corresponding to approximately 6.5 % (65,460 ha) of the surface covered by PFTs, they are the main tool for regulating forestry interventions in the region. We found a correspondence of approximately 67 % between planned management from PFTs and PFAs, confirming a reasonable level of implementation of these plans (Table S1). Accordingly, we used the planned interventions from PFTs as proxies for distinct forest management approaches across the regional forest landscape.

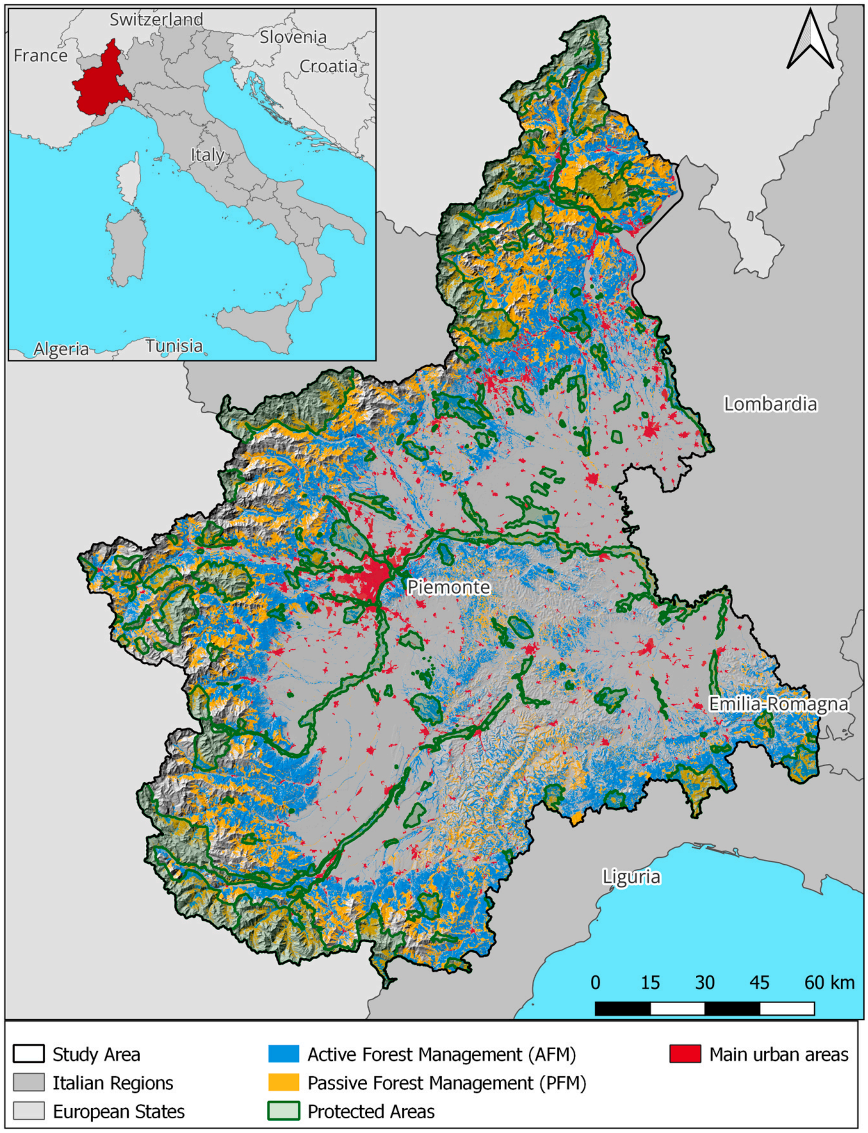

Fig. 1. Representation of the Study Area, covering the Italian region of Piedmont. Land is classified as forest land under Active Forest Management (AFM), forest land under Passive Forest Management (PFM), and Protected Areas.

2.2.2. Protected areas

We retrieved the perimeters of National and Regional Protected Areas, as reported in the official list of Protected Areas recognised by the Italian Ministry of the Environment (EUAP - *Elenco Ufficiale delle Aree Protette*), and Natura 2000 Protected Areas, from Piedmont's regional geoportal (Regione Piemonte, n.d.). Both types of protected areas account to meet the EU Biodiversity Strategy for 2030 goals of 30 % of the land under protection, and 10 % under strict protection. Where National/Regional Protected Areas and Natura 2000 areas overlapped, we counted the protected surface only once. In summary, we considered 208 National/Regional Protected Areas and 178 Natura 2000 areas, covering a total area of 462,236 ha. This corresponds to 18.2 % of the Piedmont region's surface and encompasses 18.5 % of the forest land. Most of these Protected Areas were established during the 20th century, well before the development of regional forest plans.

2.2.3. Environmental variables

Forest polygons as defined in PFTs' provided details to the type of forest landscape, based on biophysical characteristics including the dominant(s) species, which also serves as reference for silvicultural treatments under active management schemes (Regione Piemonte, n.d.). In total, 21 forest types comprised: silver fir, maple-lime-ash, lowland and montane alder, lowland and montane shrubs, invasive and pioneer species, chestnut, Turkey oak, European beech, larch and Swiss stone pine, European hop-hornbeam and manna ash, subalpine shrubs, Norway spruce, maritime pine, mountain pine, Scots pine, pedunculate oak and hornbeam, downy oak, sessile oak, black locust, afforestation plantations, riparian willow and poplar groves (Fig. 3). Topographic data on elevation and slope were extracted from a 10-m Digital Terrain Model (Regione Piemonte, n.d.). Data on travel time to cities were retrieved from Weiss et al. (2018). Travel time to cities is defined as the time required to reach the closest urban centre (contiguous areas with at least 1500 inhabitants per square kilometre or build-up areas with a minimum of 50,000 inhabitants) and we used it as a proxy of remoteness and inversely correlated with accessibility and, more broadly, human pressure. Temperature and precipitation climate data were retrieved from WorldClim (Fick and Hijmans, 2017). These are monthly climate data for the period 1970–2000 with a spatial resolution of 1 km^2. We calculated the annual average value per pixel for the variables mean temperature and annual precipitation. An overview of studies supporting this selection of environmental variables as potential drivers of carbon stock, fire hazard and biodiversity is provided in the

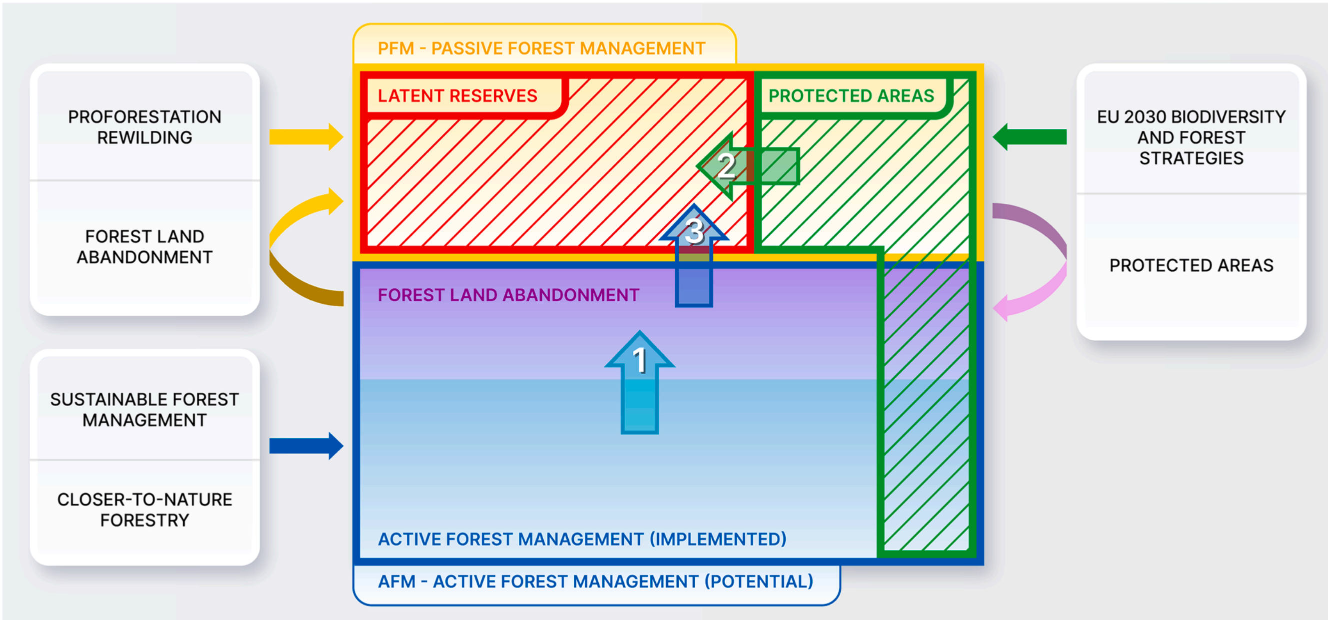

Fig. 2. Forest land classification conceptual framework. The size of the rectangles reflects proportions identified in the analyses. Processes within rectangles without an outline were not assessed in this study. Strategies, policies, and processes within rectangles with a dashed outline, associated with solid arrows, represent key drivers of forest management types, forest land abandonment processes, or the expansion of Protected Areas. Hollow arrows represent the three main proposed strategies to enhance ecosystem services provision, according to the findings from this study: 1 – retake of active forest management in abandoned forests within areas suitable for active forest management (AFM); 2 – the expansion of Protected Areas in Latent Reserves forests; 3 – the expansion of active forest management in PFM areas, where conditions are favourable.

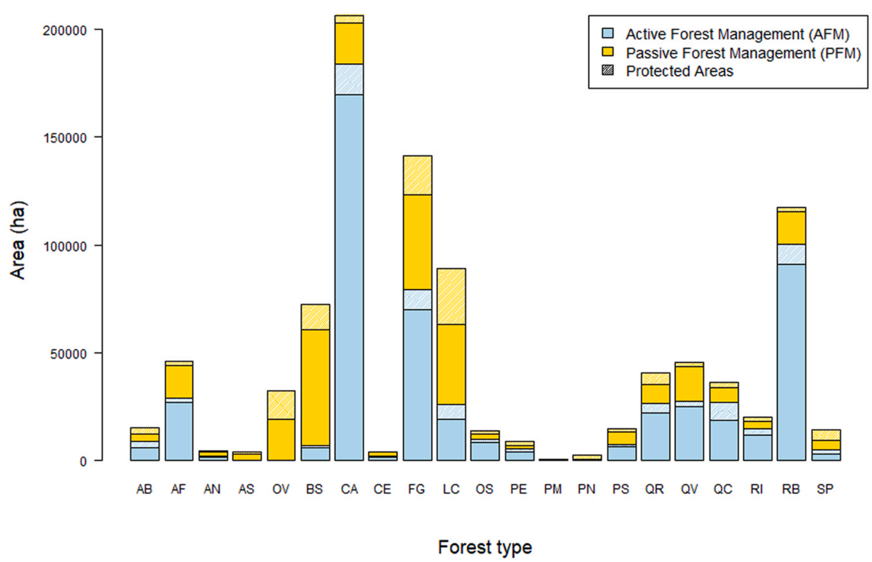

Fig. 3. Actively and passively manageable forest land, with protected land, by forest type. AB = silver fir; AF = maple-lime-ash; AN = lowland and montane alder; AS = lowland and montane shrubs; BS = invasive and pioneer species; CA = chestnut; CE = Turkey oak; FG = European beech; LC = larch and Swiss stone pine; OS = European hop-hornbeam and manna ash; OV = subalpine shrubs; PE = Norway spruce; PM = maritime pine; PN = mountain pine; PS = Scots pine; QC = pedunculate oak and hornbeam; QR = downy oak; QV = sessile oak; RB = black locust; RI = afforestation plantations; SP = riparian willow and poplar groves.

supplementary materials (SM2). However, these variables may also influence the spatial distribution of Protected Areas and management types (Baldi et al., 2017; Levers et al., 2014).

2.2.4. *Ecosystem services*

Carbon stock information was obtained from a raster dataset by Vangi et al. (2021). It refers to above and below ground carbon of all living trees in a forest area in the year 2005, with a spatial resolution of 23-m (Vangi et al., 2021). Fire hazard mitigation was measured as the absence of fire occurrence. Fire occurrence was assessed using fire perimeters as provided in the Piedmont regional geoportal (Regione Piemonte, n.d.). Perimeters were recorded by local authorities for each fire event between 2001 and 2023. Fire occurrence served as a proxy of the forest's regulatory capacity, with reduced fire occurrence reflecting enhanced structure and conditions of the forest ecosystem resulting in reduced fire hazard. Biodiversity was represented by the proxy of Shannon index for tree species diversity. This index was computed using data from the Piedmont Regional Forest Inventory (Inventario Forestale

Regionale della Regione Piemonte; Regione Piemonte, n.d.), which includes 14,164 plots distributed along a 500-m grid and a total of 404, 414 trees within those plots. The Shannon index was calculated at plot level based on tree species composition. Additional details on the resolution, reference period, and main sources of the datasets used are summarised in Table 2. Data selection was primarily driven by data availability. Given that the PFT regional forest plans span a 30-year validity period starting from 2000, for each dataset, we selected the longest temporal coverage available that could fit within this 30-year window.

2.3. Data analysis

2.3.1. Forest management types assessment through regional forest plans

Using the forest polygons included in the Regional Forest Territory Plans (PFTs), reclassified into the two classes of Active and Passive Forest Management (AFM and PFM), as explained in Section 2.2.1, we assessed the amount of Piedmont's forest land designated to the two forms of management, as well as its distribution across Protected Areas (Table 3; Fig. 1; Fig. 2) and across the different forest types (Fig. 3). We filtered polygons smaller than 0.01 ha, as many of these included topological errors. This step reduced the total number of forest polygons from 92,083 to 87,128 while keeping approximately the same total surface. To assess whether management objectives derived from PFTs could serve as a proxy for identifying areas under active or passive forest management, we compared them with their equivalents from Regional Forest Unit Management Plans (PFAs), which provide a record of the management interventions effectively carried out (See Section SM1 of the Supplementary Materials for further details).

2.3.2. Ecosystem services provision assessment

We followed multiple steps to estimate levels of ecosystem services provision associated with AFM and PFM, also accounting for the potential influence of Protected Areas. To this end, we used a point-based approach based on the centroids of the plots from the Piedmont Regional Forest Inventory. Because the number of inventory plots (14,164) was much smaller than the number of forest polygons from the PFTs (92,083), biodiversity inventory data could be associated with only about 10 % of the forest polygons. Moreover, these polygons varied highly in size, spanning up to four orders of magnitude, and were often too large (up to thousands of hectares) to be linked with point-based information from the inventory. In addition, some points fall within the same polygon, which would have required aggregating multiple points. Consequently, based on their location, we linked the inventory points to data from the PFTs (management type and forest type), Protected Areas (presence or absence), and other spatial layers on environmental variables (topography, accessibility, climate) and ecosystem services (carbon stock, fire hazard). The final dataset used in the analyses comprised 12,868 points in total, as some of the initial 14,164 points were falling outside the Regional Forest Map polygons, while others lacked biodiversity information at the tree level. The density of inventory points across the different forest classes was reasonably uniform, enabling meaningful analyses. A similar methodology was applied in previous research (Nelson and Chomitz, 2011).

To describe the different forest management classes and their relationships with ecosystem services, Protected Areas, and other environmental variables, we used the points dataset and applied (1) a Principal Component Analysis (PCA), (2) a Pearson's correlation analysis, and (3) three Generalised Linear Models (GLMs), one for each ecosystem service. While in the PCA all variables of the dataset were included, results from Pearson's correlation analysis allowed us to avoid collinearity in the GLMs by excluding variables with a Pearson correlation coefficient higher than 0.65. Due to the strong negative correlation between elevation and mean annual temperature (-0.92), we excluded the latter from the models and assumed elevation as a proxy for temperature. Within GLMs models, we adopted a normal distribution for carbon stock, a binomial distribution for fire hazard (link logit), and a gamma distribution for biodiversity (link inverse). We verified that residuals were respecting normality, independence, and homoscedasticity, and assessed the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC) curve to evaluate the performance of the binomial model. We used quadratic terms for elevation, precipitation, and travel time differently across the three models to capture the non-linear relationships observed between these environmental variables and the ecosystem services, resulting in improved model accuracy (Tables 4–6).

Table 3
Piedmont Forest Land (FL) distributed across Active Forest Management (AFM) and Passive Forest Management (PFM) for ecosystem services provision, within and outside Protected Areas (PAs). $\%^{FL}$ = percentage over the total forest land; $\%^{PA}$ = percentage over the total Protected Areas surface; $\%^{UPA}$ = percentage over the total surface outside Protected Areas (i.e., Unprotected Area); $\%^{AFM/PFM}$ = percentage of Protected and Unprotected Area over the total AFM and PFM area.

Variable / Land	Unit	Forest Land (FL)	AFM	PFM
Area	ha	932,491	563,595	368,896
	$\%^{FL}$	100.0	60.4	39.6
Protected Area (PA)	ha	172,045	69,504	102,541
	$\%^{FL}$	18.5	7.4	11.0
	$\%^{PA}$	100.0	40.4	59.6
	$\%^{AFM/PFM}$	/	12.3	27.8
Unprotected Area (UPA)	ha	760,446	494,091	266,355
	$\%^{FL}$	81.5	53.0	28.6
	$\%^{UPA}$	100.0	65.0	35.0
	$\%^{AFM/PFM}$	/	87.7	72.2

Table 2
Summary of the variables analysed in this study.

Type	Variable	Unit	Layer resolution	Reference year (s)	Source
Forest land	Forest type	/	polygons	2000	*Piani Forestali Territoriali* – Regione Piemonte, n.d.
Topography	Elevation	m a.s.l.	10x10m	2008	*Geo Piemonte* - Regione Piemonte, n.d.
	Slope	degrees	10x10m	2008	*Geo Piemonte* - Regione Piemonte, n.d.
Remoteness/ Accessibility	Travel time to cities	minutes	1x1km	2015	Weiss et al., (2018)
Climate	Mean temperature	°C	1x1km	1970–2000	Fick and Hijmans, (2017)
	Mean annual precipitations	mm	1x1km	1970–2000	Fick and Hijmans, (2017)
Ecosystem services	Carbon stock	MgC ha^{-1}	23x23m	2005	Vangi et al., (2021)
	Fire hazard mitigation (absence of fire occurrence)	/	polygons	2001–2023	*Geo Piemonte* - Regione Piemonte, n.d.
	Biodiversity (Shannon index for tree species diversity)	/	points	2000–2006	Piedmont regional forest inventory - Regione Piemonte, n.d; IPLA, (2023)
Governance	Forest Management	/	polygons	2000	*Piani Forestali Territoriali* - Regione Piemonte, n.d.
	Protected Areas	/	polygons	2022	*Geo Piemonte* - Regione Piemonte, n.d.

Table 4
Linear model for Carbon Stock (normal distribution).

Variable	Estimate	Std. Error	p-value	Significance
elevation	0.065	0.001	< 0.001	***
elevation^2	0.000	0.000	< 0.001	***
slope	0.090	0.014	< 0.001	***
travel time	0.044	0.008	< 0.001	***
precipitations	0.028	0.001	< 0.001	***
management	2.932	0.342	< 0.001	***
protection	1.582	0.537	0.003	**
management:protection	3.203	0.683	< 0.001	***

Table 5
Generalised linear model for Fire Hazard (binomial distribution).

Variable	Estimate	Std. Error	p-value	Significance
elevation	0.003	0.001	< 0.001	***
elevation^2	0.000	0.000	< 0.001	***
slope	0.042	0.006	< 0.001	***
travel time	-0.029	0.004	< 0.001	***
precipitations	0.025	0.005	< 0.001	***
precipitations^2	0.000	0.000	< 0.001	***
management	-0.306	0.135	0.024	*
protection	0.149	0.207	0.471	-
management:protection	0.032	0.276	0.908	-

Table 6
Generalised linear model for Biodiversity (Gamma distribution).

Variable	Estimate	Std. Error	p-value	Significance
elevation	-0.001	0.000	< 0.001	***
elevation^2	0.000	0.000	< 0.001	***
slope	0.001	0.001	0.406	-
travel time	0.002	0.001	0.007	**
travel time^2	0.000	0.000	0.013	*
precipitations	0.000	0.000	< 0.001	***
management	0.041	0.016	0.008	**
protection	-0.001	0.026	0.974	-
management:protection	0.008	0.033	0.808	-

We included Protected Areas (presence/absence) as an interaction term in the three GLM models to test whether they mediate the relationships between management types and environmental variables, and ecosystem services.

3. Results

3.1. Suitability for active and passive management

According to the Regional Forest Territory Plans (PFTs), approximately 40 % of Piedmont's forests are intended for passive management approaches to maximise the provision of ecosystem services (PFM), while the remaining 60 % is intended for active management (AFM; Table 3). Nonetheless, the validation through the Regional Forest Unit Management Plans (PFA), indicated a partial mismatch between planned management activities and their actual implementation (Table S1). Accordingly, the percentage of forest land that is actively managed may be lower than 60 %, because portions of AFM forest areas might have been abandoned (Fig. 2). Areas suitable for passive management (PFM) extend over 59.6 % of the total Protected Areas surface, while the remaining 40.4 % was planned to be under AFM (Table 3; Fig. 2). Protected Areas encompass 12.3 % of AFM forest land, whereas this percentage rises to 27.8 % for PFM forests (Table 3; Fig. 2). Thus, 11.0 % of the total forest land was classified as passively managed and protected, and 7.4 % as actively managed and protected ('integrate use'). Conversely, 28.6 % of total forest land seems to be passively managed and outside Protected Areas, representing potential latent reserves (Fig. 2). AFM and PFM forests within the study area, along with Protected Areas, are also represented in Fig. 1.

Forest management types (AFM, PFM) were unevenly distributed across forest types (Fig. 3). Among the three most common types, Chestnut and Black Locust forests appeared predominantly as actively managed, while Beech forests were predominantly passively managed. Larch and Swiss pine forests, along with Pioneer and invasive thickets and Shrublands, were largely passively managed. Consistent portions of Larch and Swiss pine, as well as Beech forests, were located within Protected Areas (Fig. 3).

3.2. Attributes of AFM and PFM forests

The PCA indicates that forests suitable for active management (AFM) are situated at lower elevations, smoother slopes, and more accessible locations, with warmer and drier conditions (Fig. 4). On the contrary, PFM forests are located in more remote areas, marked by harsher topography, lower temperatures, and higher rainfall (Fig. 4). AFM forests appear strongly correlated with higher tree species diversity (biodiversity) values and reduced fire hazard. In contrast, PFM are associated with increased fire hazard and lower values of biodiversity. Carbon stock does not vary with management type. For its part, Protected Areas are characterised by lower biodiversity values and are more likely to burn (Fig. 4). Indeed, the management types and Protected Areas seem to form a predominant axis along the PC2, opposed to the one given by topographical-remoteness-climate variables, along the PC1. Fire hazard is negatively correlated with biodiversity, and weakly linked to decreasing carbon stock. In other words, more biodiverse and healthier forests appear more resilient to fire. Carbon stock and forest biodiversity are orthogonal. Higher levels of carbon stock tend to be located in less accessible, higher, and colder areas. On the contrary, biodiversity and fire hazard are predominantly associated with the management type, independently of environmental conditions. On the contrary, forest types are more strongly linked to environmental conditions than forest management types. Pearson's correlations among ecosystems services and environmental variables are also shown in the Supplementary Materials (Fig. S1). The correlation analysis (Fig. S1) supports several of the relationships observed in the PCA, highlighting a strong correlation between mean temperature, and elevation and precipitation. For this reason, this variable was excluded from subsequent analyses to avoid collinearity issues.

The linear model for carbon stock (adjusted $R^2 = 0.40$) showed that all independent variables were significant, including the interaction term (Table 4). AFM was associated with higher levels of carbon stock compared to PFM. The positive interaction between management type and Protected Areas (Table 4; Fig. 5a) indicates that PAs amplify the differences in carbon stock between AFM and PFM, revealing that actively managed Protected Areas are related to higher levels of carbon stock. The GLM of fire hazard (AUC = 0.71) showed a slightly significant negative effect of AFM when compared to PFM, while the interaction with Protected Areas was not significant (Table 5; Fig. 5b). The GLM model for biodiversity (adjusted $R^2 = 0.48$) showed a significant positive effect of AFM compared to PFM, but the interaction between management type and Protected Areas was not significant (Table 6; Fig. 5c).

4. Discussions

4.1. Distribution of potential active and passive forest management

A variety of forest management approaches can be deployed to ensure the provision of multiple ecosystem services (Brockerhoff et al., 2017; Gregor et al., 2024). Acknowledging diverging strategies such as proforestation, biodiversity conservation policies (e.g., the EU Biodiversity Strategy), or closer-to-nature forestry, we adopted a dichotomous classification distinguishing between active (AFM) and passive (PFM) forest management. This framework enabled us to quantify the

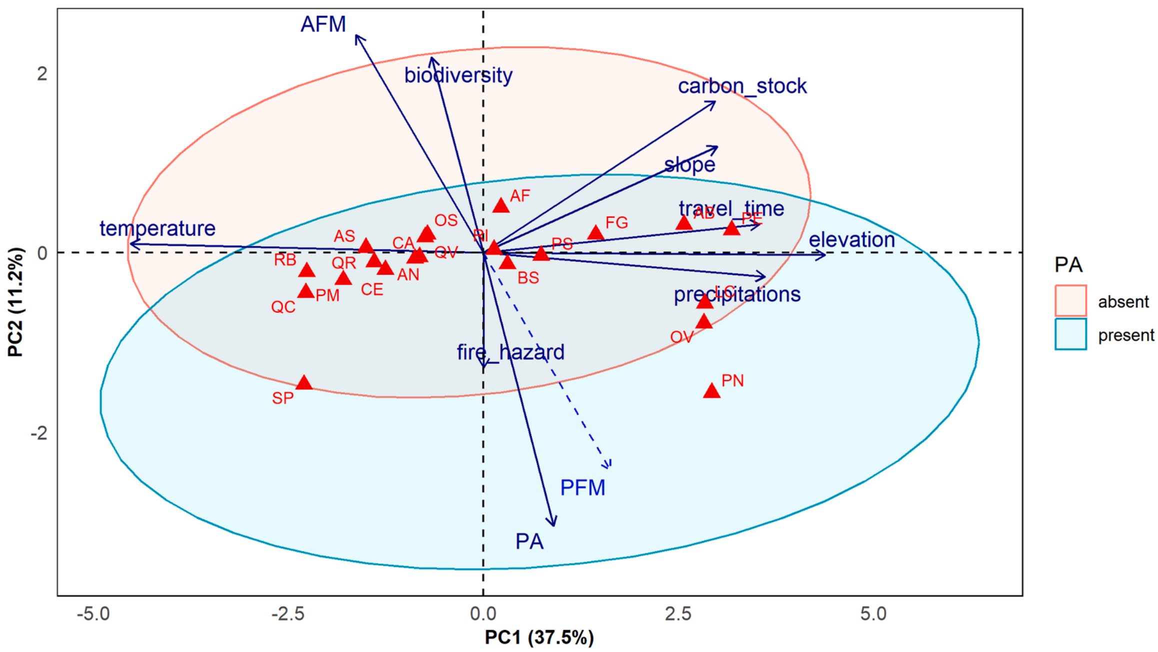

Fig. 4. PCA showing relationships among variables. Variables in capital letters represent management approaches and Protected Areas. PA = Protected Areas, 1: absent; 2: present. PFM was added as a supplementary variable (dashed line) to improve the readability of the plot. Red triangles represent forest types. AB = silver fir; AF = maple-lime-ash; AN = lowland and montane alder; AS = lowland and montane shrubs; BS = invasive and pioneer species; CA = chestnut; CE = Turkey oak; FG = European beech; LC = larch and Swiss stone pine; OS = European hop-hornbeam and manna ash; OV = subalpine shrubs; PE = Norway spruce; PM = maritime pine; PN = mountain pine; PS = Scots pine; QC = pedunculate oak and hornbeam; QR = downy oak; QV = sessile oak; RB = black locust; RI = afforestation plantations; SP = riparian willow and poplar groves.

extent to which each approach is currently deployed, their potential in delivering key ecosystem services, and their contribution to broader conservation goals, including the establishment of new Protected Areas. In the region of Piedmont, regional forest plans are essential to guide different approaches at the landscape scale for active and passive management of forests. Although forest plans do not necessarily reflect actual implemented interventions, as we assessed through a validation (Table S1), they express the potential of a landscape in delivering Ecosystem Services, indicating different management objectives (Gottero et al., 2007).

Contrarily to what was expected (Table 1), the majority of our study area (60.4 %) has the potential to be actively managed (AFM forests; Table 3; Fig. 2). However, as partially demonstrated by the validation against the Regional Forest Unit Management Plans (PFAs; Table S1), which reflect actual forest interventions, this potential remains largely underutilized. Indeed, we hypothesize that a considerable portion of AFM forests is undergoing a process of forest land abandonment which however was beyond the scope of this study to be quantified. According to our framework, ongoing or recently started forest land abandonment can affect only AFM forests, as they have been designated as such based on previous active utilisations. In contrast, forest land abandonment cannot occur in forests that have been intentionally designated to passive management approaches that do not involve interventions to modify forest structure or functions (PFM forests).

Although forest land abandonment may have uncertain outcomes on forest dynamics and ecosystem services provision (Mantero et al., 2020), it has been shown to result in predominantly negative effects in terms of fire impacts and biodiversity value, especially in southern European contexts (Guadilla-Sáez et al., 2020; Höchtl et al., 2005; Spadoni et al., 2023). At the same time, our results indicate that, despite land abandonment occurring to some extent, forests under AFM exhibit higher levels of carbon stock, biodiversity (diversity of tree species), and reduced fire hazard, compared to PFM (Fig. 4; Fig. 5). Elevated values of biodiversity and reduced fire hazard associated with AFM can be partially assumed as an effect of active forest management, as also supported by previous studies (Spadoni et al., 2023). Therefore, a key priority emerging from our findings is the retake of active forest management in currently abandoned, yet potentially manageable forests. Our findings highlight the need to resume active forest management in some of the forests that are currently abandoned yet remain potentially manageable. This issue affects forest types unevenly. For instance, Chestnut, Black Locust, and Beech forests show significant potential for active management (Fig. 3); however, these are also among the most frequently abandoned types (Bruzzese et al., 2020).

4.2. Ecosystem Services provision across different management types

Forests designated for active forest management (AFM) are associated, with statistical significance, with the highest values of the three selected Ecosystem Services (ESs) of carbon stock, fire hazard mitigation, and support to biodiversity (Fig. 5; Tables 4–6). On one hand, this pattern may reflect a cause-effect relationship, where ecosystem services are influenced by the different forest management types. This interpretation is supported by the fact that areas designated as AFM have a long history of active management, whose effects are still measurable in the present landscape. Our results suggest that, in a context of long-standing intense anthropization where most forests fall outside of the range of natural variability (Landres et al., 1999), targeted forest management interventions may enhance the provision of Ecosystem Services, including biodiversity (Motta and Larsen, 2022; Spadoni et al., 2023). Such interventions can be effectively implemented through management approaches that integrate economic and environmental sustainability with the preservation of ecological processes, such as *closer-to-nature* forestry (Larsen et al., 2022). Therefore, where topographic, accessibility and other environmental conditions permit, our findings suggest that expanding the area of active management could enhance the provision of the studied ESs in Piedmont. On the other hand, AFM forests are associated with the highest potential for ESs provision despite not being fully under active forest management (Fig. 2). Based on these findings, these areas should be prioritised for

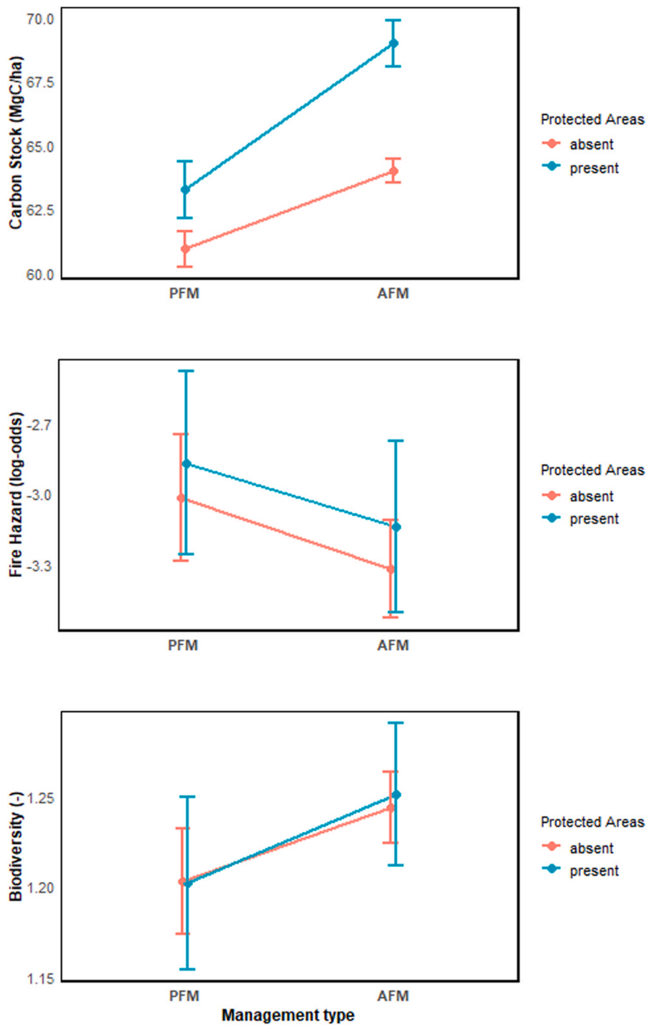

Fig. 5. Relationships between Ecosystem Services (carbon stock, fire hazard, and biodiversity) and Active and Passive management (AFM, PFM), in presence and absence of Protected Areas.

management efforts, to fulfil their potential in delivering ESs. An expansion of AFM into abandoned and, eventually, currently passively managed forests should follow a gradient of intervention intensity, balancing ecological disturbance with operational costs. Supported by well-designed policies, AFM could also stimulate employment in forested areas, contributing to the repopulation of rural and remote communities and helping counteract ongoing population flows toward urban centres (Debolini et al., 2018).

Although the three selected Ecosystem Services of carbon stock, fire hazard mitigation, and support to biodiversity seem independent or negatively correlated with one another (Fig. 4; Fig. S1), AFM forests tend to exhibit higher levels of provision regardless of the specific ES considered. Our findings support the idea that well-designed management strategies may balance multiple trade-offs among ecosystem services, avoiding the need for exclusive prioritisation (Gregor et al., 2024; Neidermeier et al., 2025). Interestingly, the PCA shows a negative correlation between fire hazard and biodiversity. In our study area, this might be due to fires being predominantly of anthropogenic origin, often linked to agricultural or illegal and uncontrolled uses, with shifting fire regimes increasingly exhibiting higher intensity, extent, and severity as a result of global change, leading to biodiversity loss (Kelly et al., 2020; Spadoni et al., 2025). At the same time, forests with higher levels of biodiversity might limit the passage of fire (Oliveras Menor et al., 2025; Puig-Gironès et al., 2025).

4.3. Protected Areas across different management types

Protected Areas are mainly (i.e., about 60 % of their total coverage) associated with potential passive management (PFM; Table 3; Fig. 2; Fig. 4). Although 33.4 % of the active interventions recorded in the Regional Forest Unit Management Plans (PFAs) occurred within forests under PFM (Table S1), this area (21,602 ha) represents only 5.9 % of the total forest area under passive management, so that PFM forests largely reflect actual passively managed forests rather than just potential ones.

Protected Areas play a crucial role in preserving pristine environments and safeguarding biodiversity in regions facing intense anthropogenic pressures (Naughton-Treves et al., 2005; Spadoni et al., 2025). However, in Southern European contexts, where forest ecosystems shaped by intense long-standing anthropization appear increasingly threatened by land abandonment, and active land management is often claimed as a solution to maintain biocultural diversity, the role of Protected Areas is more questionable (Bridgewater and Rotherham, 2019; Guadilla-Sáez et al., 2020; Santoro and Piras, 2023; Spadoni et al., 2023). Without recognition of Europe's biocultural landscapes, where current biodiversity is often intrinsically linked to traditional cultural practices, Protected Areas risk falling short of their conservation goals (Bridgewater and Rotherham, 2019; Guadilla-Sáez et al., 2020; Rotherham, 2015; Santoro and Piras, 2023). Where they impose excessively strict regulations, they might generate conflicts with local communities and contribute to the cessation of long-established active management activities, and eventually lead to passive management even in areas where active approaches could be more appropriate (Alberdi et al., 2020; Ameztegui et al., 2021; Guadilla-Sáez et al., 2020; Oldekop et al., 2016).

Within our study region, Protected Areas established during the last decades, and in most cases did not foster integrative management through effective zoning that combines strict reserves with actively managed areas (Bollmann and Braunisch, 2013). Instead, they seem predominantly associated with a segregation approach, based on the assumption that biodiversity is enhanced in the absence of human intervention. Paradoxically, our findings suggest that Protected Areas are generally associated with lower biodiversity levels, measured as diversity of tree species (Fig. 4), and tend to promote passive management practices with lower value in terms of biodiversity (Fig. 5; Guadilla-Sáez et al., 2020; Santoro and Piras, 2023).

Protected Areas (PAs) do not appear to significantly mediate the relationships between PFM and AFM and ESs (Tables 4–6; Fig. 5), although the PCA suggests some correlations between PAs and reduced biodiversity and fire hazard mitigation (Fig. 4; Dios et al., 2025; Guadilla-Sáez et al., 2020; Santoro and Piras, 2023). The exception is carbon stock (Table 4; Fig. 5), which shows a positive interaction with AFM. The negligible effect of PAs on biodiversity and fire mitigation indicate that these policy tools might not directly exert an additive effect on some particular ESs, but rather they may have a more direct influence on forest management regimes (Oldekop et al., 2016). As previously discussed, the establishment of PAs in Piedmont likely contributed to past land abandonment, which has turned into forms of planned passive management (Guadilla-Saez et al., 2020).

Our results raise doubts about the particular role of PAs in safeguarding forest biodiversity, as assessed through the proxy of tree species diversity, and reducing fire hazard. Consequently, we believe that the role of PAs in enhancing these and other ecosystem services should be critically reviewed, and that PAs should not be generally regarded as a one-size-fits-all solution (Ameztegui et al., 2021; Guadilla-Sáez et al., 2020; Jones et al., 2020; Oldekop et al., 2016; Rodríguez-Rodríguez et al., 2019; Santoro and Piras, 2023). The questionable effect of PAs on some particular ESs delivery also points out that the establishment of new PAs, as foreseen by the EU Biodiversity and Forest Strategies for 2030, may not remarkably enhance biodiversity and fire hazard mitigation based on if they are set on areas passively or actively managed. However, as new PAs may drive abandonment processes and consequent planned passive management, our study supports prioritizing PFM forests for the establishment of new PAs (Guadilla-Saez et al., 2020; Santoro and Piras; 2023). Conversely, imposing new PAs in AFM land might reduce the area available for active forest management, thereby limiting its higher potential in delivering ESs. Indeed, we found that 28.6 % of the entire forest land is passively managed and located outside Protected Areas (Table 3; Fig. 2), and our results suggest that these areas represent latent reserves (Portier et al., 2021), offering a potential for the establishment of new PAs (Mouillot et al., 2024; Testolin et al., 2025).

Nonetheless, the positive interaction with carbon stock suggests that the establishment of PAs could also target some AFM forests to ensure higher carbon stock values. These areas host the highest biomass productivity potential that PAs could contribute to safeguarding (Favero et al., 2020). In this sense, our findings highlight the benefits of an integrative approach that combines protection with adaptive, low impact management strategies (Bollmann and Braunisch, 2013; Bütler et al., 2013; Zeller et al., 2022). Hence, new PAs in PFM areas should be planned through zoning schemes that also include portions dedicated to active management, in order to enhance ESs such as carbon stock.

4.4. Limitations

Our study adopted a dichotomous approach to represent forest management types, classifying them into the two broad categories of active and passive management. While this simple classification represents one of the innovative aspects of this paper, it also involves some limitations. First, the two classes refer to potential active and passive management, but each group encompasses different processes that we were unable to disentangle. For instance, we did not assess the process of forest land abandonment that may occur within AFM forests, nor did we recognise high natural value forests that could be embedded within PFM areas. In addition, namely within AFM forests, it would be valuable to further distinguish among management approaches, such as short-rotation forestry, sustainable forestry, or protection forests, to assess their specific contributions to ESs provision. Second, this study focused on forest management classes patterns at the regional scale without exploring intra-class variability in ESs provision depending on environmental variables. Such analysis could have come out with more targeted management recommendations. Additionally, we did not assess how different configurations of combined active and passive management across Protected Areas, under an integrated management framework, might optimize ESs delivery. Third, we acknowledge that environmental factors beyond topography, accessibility, and climate, may influence both management type and ecosystem services, and may interact with management in driving ecosystem services provision. For instance, AFM forests are more present at lower elevations, where fire suppression capacity is higher. To account for such potential confounding, future studies might include approaches such as stratified analyses by elevation or matching techniques that compare AFM and PFM areas with similar environmental attributes. Finally, our approach was limited to the evaluation of three ecosystem services, mostly due to data availability constraints. Including additional services, such as hydrological regulation, soil erosion control, recreation, and cultural values, might have led to different or more nuanced conclusions. Moreover, the ES of biodiversity was assessed exclusively through the Shannon index of tree species diversity. While this index offers a useful proxy, biodiversity is a multifaceted concept that has many other components not included in our analyses. Future work should enlarge the selection of ecosystem services and broaden the representation of biodiversity. Using single indicators may overlook key mechanisms or lead to biased interpretations of complex processes or aspects such as fire and biodiversity. For instance, fire, at the side of its occurrence, could be characterised also by fire intensity and severity; carbon stock could include additional pools such as soil carbon; and biodiversity could integrate aspects beyond tree species diversity, such as age-class diversity, structural heterogeneity, and faunal components. Broadening these dimensions would reduce the risk of underestimating multifaceted processes as, for instance, fire occurrence alone may be strongly influenced by suppression efforts, whereas including fire intensity could confirm or not whether passively managed forests are more susceptible to extreme fire behaviour.

5. Conclusions

Focusing on the Italian region of Piedmont as a representative area of the Southern European context, this study found that, based on regional planning documents, approximately 60 % of its forest landscape is suitable for active forest management (i.e., approaches involving interventions of different intensity to regulate forest structure and functions), while the remaining 40 % is designated for passive management, characterised by no-intervention. However, this potential is not consistently realised, as ongoing processes of forest land abandonment are affecting areas previously managed and with a potential for active forest management. Areas suitable for active management, compared to areas designated for passive management, were associated with higher levels of Ecosystem Services (ESs) provision as measured by carbon stock, fire hazard prevention, and biodiversity (diversity of tree species). The presence of Protected Areas did not affect these relationships remarkably, although they may act as drivers of passive management. Based on our findings, we identified the following priorities to optimise forest ecosystem services provision through tailored management approaches. First, we support reintroducing active forest management in currently abandoned yet potentially manageable forest areas, namely within Chestnut, Black Locust, and Beech forest types. Resources should be invested in these areas, as they are among the most accessible and offer the highest potential for ESs delivery. Second, we suggest prioritizing areas designated for passive forest management and unprotected (i.e., latent reserves) as suitable candidates for the establishment of new Protected Areas to meet EU Forest and Biodiversity Strategies goals. In fact, PAs do not significantly alter the ESs potential linked with different management types, but they could reinforce trends towards abandonment and consequent planned passive management. Third, where environmental conditions are favourable, we recommend expanding the area designated for active management, in order to further enhance the provision of ESs (Fig. 2). Our findings and the resulting management recommendations can be further improved by addressing the limitations of this study. In particular, by refining the forest management types classification, distinguishing between potential and actually implemented approach, passing through the identification of the abandonment process and of high natural value forests. Or even, by introducing additional subclasses within the broad classes of active and passive management, such as closer-to-nature forestry or intensive short-rotation monocultures. Improving and enhancing the forest management types classification could also support a more targeted assessment of the provision of ESs associated with each class. In addition, our findings support the prioritization of integrative management, and further research could explore how different combinations of active and passive management may jointly further enhance ESs provision. Finally, complementing the analyses with additional ecosystem services and integrating additional dimensions of biodiversity would contribute to a more comprehensive and representative analysis.

CRediT authorship contribution statement

Cinzia Passamani: Writing – review & editing, Methodology, Data curation. **Imma Oliveras Menor:** Writing – review & editing, Supervision, Methodology, Data curation. **Sergio de Miguel:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Kirschner Judith A.:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Gilles Le Moguédec:** Supervision, Formal analysis, Data curation. **Franco Gottero:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Piergiorgio Terzuolo:**

Writing – review & editing, Supervision, Investigation, Conceptualization. **Jose V. Moris:** Writing – review & editing, Software, Methodology, Data curation, Conceptualization. **Gian Luca Spadoni:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation. **Renzo Motta:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Davide Ascoli:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

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.

Acknowledgments

The authors wish to thank Costanza Borghi, Elia Vangi and Gherardo Chirici for sharing data on Carbon Stock; and Daniele Monchiero for helping with designing Fig. 2. This paper/research has been funded by the European Union as part of the FIRE-ADAPT project, Grant Agreement Nº 101086416. DV activities were funded by the REWILD-FIRE - Rewilding policies for carbon sequestration under increasing fire risk - project funded by Next Generation EU, PRIN PNRRR 2022, project code MUR: 2022R7F259 – CUP: D53D23004850006. The content of this document does not necessarily reflect the official opinion of the European Commission. Responsibility for the information and views expressed herein lies entirely with the authors. JVM acknowledges the funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101147417.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123387.

Data availability

Data will be made available on request.

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