Mapping of ecosystem services provided by deadwood islands in managed forests: An application in the Italian Alps

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Received: 1 August 2025 / Accepted: 2 December 2025

Abstract. Over the past few decades, both scientific community and policy makers focused on ecosystem services provided by forests due to their positive impact on human well-being and quality of life. In literature, there is a broad consensus that assessing and mapping ecosystem services is one of the most demanding challenges to address, but at the same time a key tool for effective forest management. This study aims to develop a method suitable to assess and map ecosystem services provided by deadwood islands located in managed forests. To this end, a geospatial analysis was developed in a case study in Italy to conduct an integrated investigation of ecosystem services provided inside and outside the deadwood islands (timber production, stand stability, outdoor recreation, biodiversity conservation). The innovative nature of this study is that it assessed ecosystem services provided by the deadwood islands within managed forests, an aspect that has not yet been investigated in the international literature. The results showed a positive correlation between the four ecosystem services provided by forests and in particular between: timber production and biodiversity conservation; outdoor recreation and stand stability; biodiversity conservation and stand stability. In addition, the results highlighted that the interventions implemented in the deadwood islands have a positive effect on the biodiversity conservation without compromising the provision of other ecosystem services. From a practical standpoint, the results of this study provide forest managers with insights into the impacts of deadwood islands on a wide range of ecosystem services, not just biodiversity. By doing so, managers can better understand the real impacts of this management system on forests.

Keywords: production forests; biodiversity conservation; stand stability; outdoor recreation; geospatial analysis.

1. Introduction

In recent decades, the concept of ecosystem services (ESs) – defined as the direct and indirect contributions of ecosystems to human wellbeing (TEEB, 2010) – has become the *leitmotiv* of European Union's environmental policies (Maes et al., 2012). The EU 2020 Biodiversity Strategy integrated the sustainable use of ESs as a cornerstone of human economic development (Maes et al., 2013), while the new EU Forest Strategy for 2023 stressed the importance to maintain and improve the provision of ESs by European forests (EC, 2021). In particular, the Action 5 of the EU Biodiversity Strategy to 2020 stressed the importance of mapping and assessing the state of ecosystems and their services across the country, assessing the economic value of these services, and promoting the integration of these values into accounting and reporting systems at EU and national levels by 2020 (Maes et al., 2020). Recently, the European Commission (EC) published the guidelines on payment schemes for forest ESs (EC, 2023), in which the managerial and economic importance of the multiple services provided by forests to society (e.g., habitats for biodiversity, water purification, and regulation of floods and climate) is reiterated and emphasized. Furthermore, the Guidelines on Closer-to-Nature Forest Management (2023) highlighted the positive effects of closer-to-nature forest management on biodiversity restoration and conservation, forest productivity and resilience to climate change, soil and water preservation. In 2024, the Nature Restoration Law (Regulation EU 2024/1991) emphasized the need to implement measures to restore degraded forest ecosystems (art.10) considering key indicators such as biodiversity (e.g., standing dead trees, lying deadwood, forest connectivity) and carbon cycle (e.g., organic carbon stock).

The theoretical concept of ESs was introduced into the environmental management by Ehrlich and Ehrlich in 1981. Recently, the ESs have been studied from multiple perspectives: from natural-environmental sciences (Krsnik et al., 2023), to legislative (Phelps et al., 2015), to social and economic ones (De Meo et al., 2018).

Over the last few years, the notion of ESs has gone from being a purely theoretical concept to a practical-applicative one in forest management planning (Baskent et al., 2020; Müller et al., 2020). It can be said that the precondition of the multifunctional forest management paradigm is represented by a combination of benchmarking sustainability and management planning, aimed at the provision of a multitude of ESs such as wood and bioenergy production, protection against natural hazards, carbon sequestration, and biodiversity (Biber et al., 2020; 2021; Akujärvi et al., 2021; Thrippleton et al., 2023). To integrate ESs into forest management planning choices, the assessment of ESs in time and space is of fundamental importance as well as considering the relationships (trade-offs or synergies) between ESs (Obiang Ndong et al., 2020). As emphasized by Peña et al. (2015), the explicit mapping of ESs is considered one of the main conditions for the inclusion of the concept of ESs into decision-making process. Spatially-explicit assessment of ESs using GIS-based approaches is a key point to incorporate ESs among use allocation and management criteria (Tiemann & Ring, 2022). In fact, the EU 2020 Biodiversity Strategy also recognized the potential of mapping ESs for policy support, as maps are valuable representations of real conditions and powerful tools for communicating complex data and information in a simple way. In literature, Schägner et al. (2013) pointed out that over 140 studies have mapped ESs between 1995 and 2011, while recently studies on the assessment and mapping of ESs provided in managed forests have further grown (Paletto et al., 2015b¸ Thrippleton et al., 2023). In a literature review, Obiang Ndong et al. (2020) focused on characteristics of the spatial and temporal analyses of relationships between ESs in the studies published from 1998 to 2017. Based on the international studies, there is a knowledge gap regarding the assessment and mapping of ESs provided by forest areas with high biodiversity value (e.g., deadwood islands) compared to managed forests for timber production or recreational purposes.

The maintenance and protection of the deadwood islands – also known as Saproxylic Habitat Sites (SHSs) or *îlot de senescence* – is one of the most important biodiversity conservation measures that can be adopted in the production forests (Aerts, 2013; Mason & Zapponi, 2016). To maintain and improve forest biodiversity, deadwood – defined as all non-living woody biomass not contained in the litter including woody debris, snags, standing dead trees, and stumps (Hagemann et al., 2009) – is a key component as emphasized in many studies (Lassauce et al., 2011; Paletto et al., 2014; Lombardi & Mali, 2016). However, deadwood plays a key role in forests positively influencing soil fertility and productivity, protecting against rockfalls and landslides, facilitating natural regeneration of forests, and contributing to climate change mitigation by temporary storing carbon (Herrero et al., 2016; Bayraktar et al., 2020). As highlighted by Lachat and Bütler (2008), SHSs are small and permanently unmanaged patches capable of providing sustainable habitats (e.g., microhabitat trees, lying deadwood, standing dead trees, old stumps) for saproxylic organisms. However, these areas aimed at the conservation of biodiversity can give rise to trade-offs with other ESs provided by managed forests. In particular, some studies highlighted the trade-offs between wood production and biodiversity conservation with special regard to the amount of coarse deadwood and the abundance of large trees (Biber et al., 2020). Other studies have found a trade-off between recreation services and biodiversity preservation due to the fact that visitors are more likely to carry out recreational activities in areas with good infrastructure and convenient transportation (Ge et al., 2022). Therefore, forests with a high naturalness value are the least suitable for recreational activities which can also have a negative impact on biodiversity (Ament et al., 2017). However, it is important to highlight that SHSs have peculiar conditions compared to managed forests. First of all, SHSs are areas where timber is not harvested, and left as deadwood useful for saproxylic species, or is harvested only in order to create gaps favourable to increase locally the understory plant richness. Nevertheless, it is now widely recognized that a multifunctional forest management is what allows reconciling the needs of timber production with the multitude of additional services offered by forest

(Schwaiger et al., 2019). In addition, in the eyes of visitors the high amount of deadwood inside the SHSs may seem like a sign of mismanagement or as a threat to forest health (Sacher et al., 2022). Some European studies have shown that lying deadwood and standing dead trees in a forest are generally disliked by visitors from an aesthetic point of view (Golivets, 2011; Jankovska et al., 2014) as they are not associated with the concept of biodiversity conservation (Paletto et al., 2023a). Conversely, in extra-European contexts some studies have shown a positive perception of the younger generations towards diversified forests with lying deadwood and standing dead trees (Bayraktar et al., 2024, 2025). Besides, the silvicultural interventions within the SHSs for the creation of microhabitat trees and lying deadwood, and the opening of gaps in the forest cover can influence stand stability and hydrogeological protection (Bachofen & Zingg, 2001; Selkimäki et al., 2020). Therefore, it appears relevant to investigate the potential trade-offs and synergies between biodiversity conservation and other ESs in forests with a high biodiversity value, such as deadwood islands.

Starting from these considerations, the objective of this study is to develop a method suitable to assess and map ESs in the forest areas dedicated to biodiversity conservation, such as deadwood islands. The ecological questions that this study addresses are: What is the importance of the ESs provided by deadwood islands within managed forests? How can ESs provided by deadwood islands be biophysically assessed and spatially located to support decision makers? To this end, the research was implemented in one study area of the LIFE SPAN project (LIFE19 NAT/IT/000104) which aims to preserve saproxylic biodiversity in production forests through the creation of a network of SHSs. The innovative aspect of the present study is to assess ESs provided by the deadwood islands within managed forests, an aspect that has not yet been investigated in the international literature.

2. Materials and Methods

2.1. Study area

The study area is the Cansiglio Orientale forest (46 067° N, 12 405° E), located in the province of Pordenone (Friuli Venezia Giulia Region) in north-eastern Italy (Fig. 1). The Friuli Venezia Giulia Region is the owner of the Cansiglio Orientale forest (henceforth COF) since 1966.

The COF covers over 1,500 ha in three municipalities (Caneva, Polcenigo, Budoia) located in the Carnic Prealps, at an altitude between 1,118 and 1,694 m a.s.l. More than 98% of the COF is covered by forests – European Beech (*Fagus sylvatica*)-Silver Fir (*Abies alba*)-

Norway spruce (*Picea abies*) mixed forest (37%), European beech-dominated forest (29%), and Norway spruce-dominated forest (15%) – while only 1.4% is covered by grasslands (meadows and pastures). The timber traded annually mainly derives from prescribed yield of Forest Unit Management Plan-FUMP (about 2,800 m^3) and in lesser quantity from phytosanitary interventions (about 700 m^3). In Italy, the FUMP is the forest compartment/stand aimed to define technical plan and management practices of each individual forest Ownership (Paletto et al., 2015a). The FUMP of the COF is divided in 91 units with an average surface of 17.17±12.29 ha, included in a range between a minimum of 0.30 ha and a maximum of 92.84 ha. As a result, the COF can be considered as a forest with a main productive function, which is managed according to the principles of forest multifunctionality and the close-to-nature approach. The silvicultural treatment applied in the uneven-aged European Beech-Silver Fir-Norway Spruce mixed forests is the individual selection system of trees with a diameter equal to or greater than 55 cm. On the other hand, the even-aged European beech-dominated forests were managed through the strip-and-group felling system.

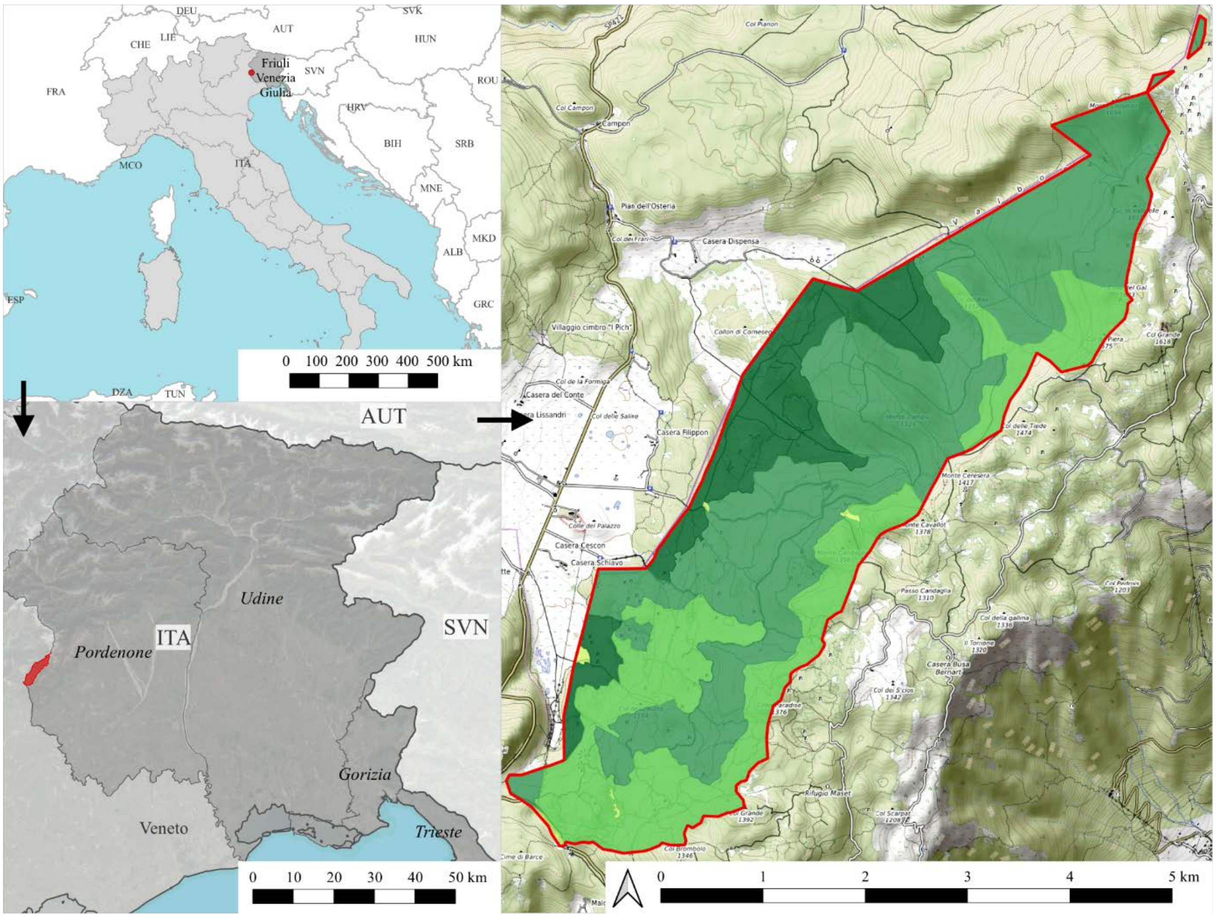

Figure 1. Location of the study area (the Cansiglio Orientale forest) in the Friuli Venezia Giulia Region, Italy

The average annual temperature is 5.1°C and the number of rainy days per year is about 100. The highest rainfall is in November (average of 230 mm), while December and January are the months with the lowest rainfall (average of 100 mm). The ground is covered with snow from November to mid-March, with an average annual snowfall of 60–150 cm.

2.2. Research Framework

The main objective of this study was to map the biophysical values of ESs provided by the SHSs. The proposed methodology was implemented and tested in the COF in which twenty-one new SHSs of approximately 2.5 ha were created for biodiversity conservation purposes by the LIFE SPAN project. In each SHS, the following interventions have been implemented (see Fig. 2):

- Creation of new microhabitat trees: on average, 10% of large living trees were involved in the creation of new microhabitats such as cavities, water-filled holes, girdled and uprooted trees;
- Creation of uprooted trees and lying deadwood in order to exceed the minimum threshold of 20 m^3 of deadwood per hectare;
- Opening gaps: all trees in an area of 0.15 ha are cut and removed as commercial timber corresponding to an average volume of approximately 150 m^3 to locally increase the understory plant species richness.

The aforementioned interventions and thresholds were defined by the LIFE SPAN project on previous experimental experience carried out in other Italian sites (Zapponi et al., 2014). The impacts of interventions on forest ecosystem functions were quantified considering the definition and classification proposed by De Groot et al. (2002). Ecosystem functions can be defined as the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly (De Groot et al., 2002). Those authors described 23 ecosystem functions, while in the present study the following ESs for each category were estimated: building and manufacturing (i.e. timber) in the production function; disturbance prevention in the regulating functions (i.e. hydrogeological protection); provision of suitable living spaces for wildlife species in the habitat functions (i.e. biodiversity and habitat); and recreation in information functions (i.e. outdoor recreation). Based on the interventions implemented in the SHSs and the categories of ESs, the potential impacts for each type of intervention on individual ecosystem services have been hypothesized and described in Table 1. The main steps for the biophysical assessment and spatial analysis of the selected ESs are explained in the following paragraphs, while Table 1 summarises the input data, output data and the method adopted for each ecosystem services..

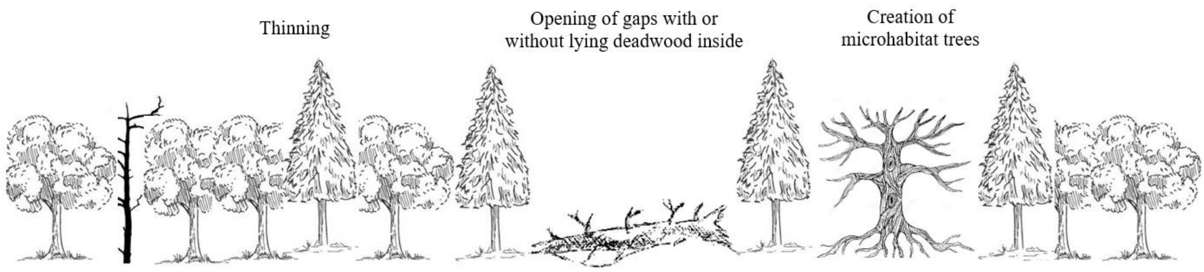

Figure 2. Graphical representation of the Saproxylic Habitat Site (SHS) structure

Table 1. Hypothesized potential impacts of different interventions in Saproxylic Habitat Site (SHS) on different ecosystem services.

Interventions in the SHSs	Ecosystem services	Potential impacts
Creation of new microhabitat trees	Timber production	Subtraction of living trees from timber production
	Hydrogeological protection	Change of the slenderness coefficient
	Outdoor recreation	Visual impact due to the presence of standing dead trees
	Biodiversity and habitats	Providing shelter and habitat for some saproxylic species
Creation of uprooted trees and lying deadwood	Timber production	Potentially productive living trees transformed into uprooted trees and lying deadwood
	Hydrogeological protection	Change of the slenderness coefficient
	Outdoor recreation	Visual impact due to the presence of uprooted trees and lying deadwood
	Biodiversity and habitats	Providing shelter and habitat for some saproxylic species
Opening gaps	Timber production	Harvesting and marketing of wood cut in the gaps
	Hydrogeological protection	Increased risk of erosion or landslides
	Outdoor recreation	Decreasing canopy cover and landscape

		diversification
	Biodiversity and habitats	Potential increase in floristic biodiversity

Table 2. Input data, output data, method adopted, and spacialization unit for the ESs considered in the study.

Input Data	Source/method	Output Data	Spazialization unit
Timber production (provisioning services)			
Volume and biomass prescribed (m^3 ha^{-1} yr^{-1})	Forest Management Plan (FUMP) and algorithms of Italian NFI	Prescribed yield from FMUP (m^3 ha^{-1} yr^{-1})	Forest management unit (ha)
Volume and biomass harvested (m^3 ha^{-1} yr^{-1})	Field measurements of the LIFE SPAN project and algorithms of Italian NFI	Extraordinary yield in the SHSs (m^3 ha^{-1} yr^{-1})	SHSs areas (ha)
Stand stability (regulating services)			
Tree diameter at breast height (m)	LiDAR data	Slenderness Coefficient at stand level	Homogeneous areas of Slenderness Coefficient (ha)
Tree height (m)			
Outdoor recreation (cultural services)			
Managed forest landscape	Questionnaire administered to the visitors	Ranking visitors' preferences assigned to managed forests and SHSs (5- point Likert scale)	SHSs areas (ha)
SHS landscape			
Land uses	Focus group with experts	Weight assigned to indicators (priority values AHP)	Grasslands area (ha)
Forest type			Forests area (ha)
Water elements			Hydrological network (buffer zone of 20 m)
Paths and roads			Paths and roads network (buffer zone of 10 m)
Accommodation			Forest types area

facilities			(ha)
Points of interest			Accommodation facilities (buffer zone of 1 km)
			Points of interest (buffer zone of 1 km)
Biodiversity and habitat provision			
SHSs	Focus group with experts	Weight assigned to indicators (priority values AHP)	SHSs area (ha)
Land uses			Grasslands area (ha)
Forest type			Forests area (ha)
			Forest types area (ha)
Ecotones			Ecotones (buffer zone of 10 m between grasslands and forests)
Water elements			Hydrological network (buffer zone of 50 m)

2.2.1. Timber production

Biophysical assessment Timber production was assessed because it can be considered as the most important ES of the forest production function (Duncker et al., 2012; Schwenk et al., 2012). Timber production was estimated considering the volumes of timber harvested through ordinary forestry interventions, within the units of the Forest Unit Management Plan (FUMP) during its 15-year duration (2022-2036), and the specific silvicultural interventions within the SHSs (years 2022-2023).

In the SHSs where timber has been removed during the opening of the gaps and marketed, this volume has increased the value of the provisioning service. Conversely, where trees have been cut down and not removed, this volume has increased the deadwood volume as a key component of supporting services (trade-off between timber production and biodiversity conservation).

From a methodological point of view, timber production was quantified through the following steps. Volume (m^3) and biomass (kg) of both stem, large and small branches were estimated using the algorithms of the Italian National Forest Inventories (NFI) by species (Gasparini & Tabacchi, 2011). The allometric equations used in the estimation of the volume and biomass of the three main species (i.e., European beech, Norway spruce, silver fir) at stand level are thus synthesizable (Eqs. (1)-(3)):

$$V_i = b_0 + b_1 \cdot d^2 \cdot h + b_2 \cdot d \quad (1)$$

$$Dw_{1i} = b_0 + b_1 \cdot d^2 \cdot h + b_2 \cdot d \quad (2)$$

$$Dw_{2i} = b_0 + b_1 \cdot d^2 \cdot h + b_2 \cdot d \quad (3)$$

where: V_i is the volume for the *i*-th species (m^3); Dw_{1i} is the biomass of stem and large branches for the *i*-th species (kg); Dw_{2i} is the biomass of small branches for the *i*-th species (kg); *d* is the diameter at breast height (cm); *h* is the tree height (m). The coefficients b_0, b_1, and b_2 are assigned according to Gasparini and Tabacchi (2011).

Spatial analysis

The total prescribed yield (m^3) was assigned to each unit of the COF from a spatial point of view based on the current FUMP. Consequently, the total prescribed yield of each unit has been divided by the number of years foreseen in the FUMP (i.e., 15 years) to obtain the annual prescribed yield (m^3 yr^{-1}). After that, the extraordinary yield inside the SHSs was assigned to the corresponding SHS based on the timber removed and marketed.

The biophysical map of the timber production in t the COF was obtained by considering ordinary and extraordinary yield per management unit.

2.2.2. Stand stability

Biophysical assessment

Stand stability was selected in the disturbance prevention function because it is strictly related to the hydrogeological protection provided by forests (Dorren et al., 2004). In other terms, stand stability is the probability that significant damage occurring to the considered forest stand in a certain interval of time (Herold & Ulmer, 2001). As highlighted in the literature, several variables contribute to the assessment of stand stability, such as tree species, slenderness coefficient, crown length and form, root anchorage, vertical stand structure (Gardiner et al., 1997; Herold & Ulmer, 2001).

In this study, the Slenderness Coefficient (hereinafter *SC*) was adopted for the assessment of stand stability, as it results the most commonly used variable in studies on forest resilience to natural hazards, such as snow and wind (Skrzyszewski & Pach, 2020). Tree *SC* is a dimensionless value based on the ratio of tree diameter at breast height (*Dbh*) and total tree height (*H*), for which low values represent high stand stability (Vacchiano et al., 2016). Usually, the *SC* is used as the main indicator of single-tree mechanical stability (Schelhaas et al., 2007), but at stand-level it can be considered as a fair proxy of the ability of the forests to maintain the protective function and general mechanical stability. According to Cantiani and Chiavetta (2015) and Marchi et al. (2018), the Eq. (4) was adopted to calculate the *SC* for each tree in the units of COF:

$$SC_i = \frac{THT_i}{Dbh_i} \tag{4}$$

where: SC_i is the slenderness coefficient of the *i*-th tree; THT_i is the total height of the *i*-th tree (m); Dbh_i is the tree diameter at breast height of the *i*-th tree (m).

SC of the single trees in the COF was assessed using LiDAR data (LAS point cloud, courtesy by Friuli Venezia Giulia Region, https://irdat.regione.fvg.it/consultatore-dati-ambientali-territoriali). According to Šmudla (2004) and Adeyemi and Adesoye (2016), the *SC* values of single trees were divided into three classes: $SC \leq 80$ represents high stand stability (class 1); $80 < SC \leq 90$ moderate stand stability (class 2); $SC > 90$ low stand stability (class 3).

Spatial analysis

From a spatial point of view, a moving window raster analysis was used with the aim of aggregating single trees in areas with homogeneous SC value. To reduce the abundant presence of very small polygons (the so-called “salt-pepper” effect), areas less than 1000 m^2 were aggregated (“diluted”) to the nearest larger polygon and assigned to the corresponding SC class. In this way, the ex-ante slenderness map of the COF was obtained. For each SHS, an average value of *SC* was estimated after the realization of the silvicultural interventions (i.e. creation of habitat trees and lying deadwood, opening of gaps). The new SC values were attributed to the corresponding units and the ex-post slenderness map of the COF was obtained. For additional information on spatial analysis of stand stability see Sergiacomi et al. (2024).

2.2.3. Outdoor recreation

Biophysical assessment

Cultural services are all non-material benefits, which derive from the ecosystem and which people can enjoy (MEA, 2005). Among the cultural services, many studies focused on the outdoor recreation in forests as it is the one with the greatest social and economic positive impacts (Caglayan et al., 2020; Riccioli et al., 2020; Termansen et al., 2013).

In this study, outdoor recreation in the COF was assessed through a survey questionnaire administrated face-to-face (June - September 2023) to a sample of visitors (N=119). The survey was aimed at analysing visitors' visual-aesthetic preferences towards forests managed for timber production versus forests managed for biodiversity conservation. To this end, in the questionnaire two images of the COF managed for different purposes (timber production vs. biodiversity conservation) were showed to the respondents. The first image showed the COF without deadwood as in forests managed for timber production, while in the second one with a high amount of deadwood – as in the SHSs – was shown. Respondents were asked to assign their preferences from an aesthetic point of view using a 5-point Likert scale format (from 1 very ugly aesthetic landscape to 5 very nice aesthetic landscape). The results of the survey were used to define the ranking of visitors' preferences using it as a proxy for the recreational attractiveness of the forests managed differently. In addition to the question used in the present analysis, the survey allowed for a broader assessment of outdoor recreation in the COF (for further information see Sergiacomi & Paletto, 2025).

Spatial analysis

The biophysical map of the outdoor recreational value was realized through a raster analysis implemented with the IDRISI Selva 17.0 software (trial version). The spatial distribution of values was done based on the fuzzy theory which assumes that the judgment on spatial issues must be characterized by a certain degree of uncertainty to avoid establishing fixed definitions and boundaries (Malczewski, 1999). The uncertainty is incorporated by establishing fuzzy sets (classes of biophysical and geographical characteristics) which was formulated trough a linear fuzzy membership function.

Seven indicators related to the recreational attractiveness were included in the spatial analysis. The concept of fuzzy logic, adopted for some of the indicators used in this study, was introduced by Zadeh (1965). Biber et al. (2021) stressed the usefulness of adopting the fuzzy function for the development of indicators in the field of forest ESs assessment. Those authors argued that this utility is greater for services that can be evaluated mainly in a qualitative way, such as in the case of cultural (e.g., recreation) and supporting (e.g., biodiversity) services. The fuzzification process aimed to normalize the considered indicators in a continuous variation between 0.00 and 1.00, by using different so-called membership functions, such as the monotonically decreasing or increasing linear functions adopted in this study (Fig. 3). The coefficient values of the fuzzy functions for the recreational indicators are shown in Annex 1.

Accommodation facilities and points of interest were mapped as the most attractive elements such as structures and accommodation facilities, panoramic points, nature emergencies (Lee et al., 2010; Sergiacomi et al., 2022). In addition, accommodation facilities and points of interests can provide an excellent opportunity to sensitize visitors experiencing the local culture (Lončarić et al., 2021). At the methodological level, a buffer zone of influence was drawn around accommodation facilities and point of interest to consider the reinforced attractiveness of the surrounding area according to a decreasing linear fuzzy function (see Fig. 3) between 0 and 1 km (Table 1).

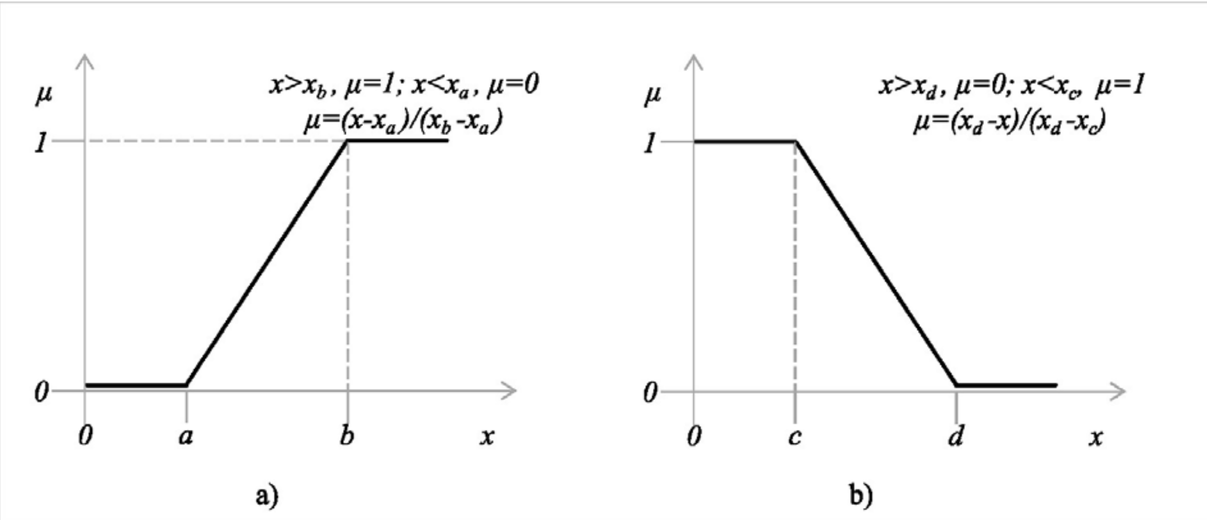

Figure 3. Linear membership functions: (a) monotonically increasing; (b) monotonically decreasing

A second recreational indicator is the paths and trails network considered as a positive element for the recreational attractiveness of a forest site. As found by De Meo et al. (2015), forest visitors appreciate the naturalness of the landscape, but without having to forego basic infrastructure such as path and trails. In addition, the types of recreation that Skłodowski et al. (2013) consider "active" (i.e., running, bicycling, walking, hiking, etc.) is more frequently practiced on paths and nature trails. Also in this case, a decreasing linear fuzzy function (see Fig. 3) among 0 m and 10 m is considered (Table 1).

Grasslands have been identified as a further indicator that influences the recreational attractiveness of a site according to the literature (Bengtsson et al., 2019; Garrido et al., 2017). Besides, Marzetti et al. (2011) observed that visitors tend to prefer the presence of grasslands within the forests, both because they create a landscape diversification and because they allow preserving semi-natural habitats, increasing biodiversity.

Water elements (e.g., ponds, streams, wetlands) have been considered as the fourth indicator with appositive effect on the recreational attractiveness. In fact, it is widely recognized the importance of the water elements in forest (Pastorella et al., 2017), regardless of the activities that can be practiced such as fishing, sailing and canoeing (Abildtrup et al., 2013). Also in this case, a decreasing linear fuzzy function (see Fig. 3) between 0 m and 20 m (Table 1), which was considered as the maximum distance at which to visually appreciate a water element, was taken into account.

The last indicator considered in the study was the forest composition distinguishing between: pure conifer forests, pure broadleaved forests, and mixed forests. In literature, many studies found that the recreational value of the mixed forests is higher compared to pure forests (Abildtrup et al., 2013; Grilli et al., 2014). Termansen et al. (2013) found that recreational choices are affected by tree species composition, with broadleaved forests being preferred to conifer forests.

Finally, the SHSs was considered as the less attractive indicator based on survey data. In fact, visitors prefer forests with a low amount of deadwood compared to areas with a high amount of deadwood in accordance with the results of this survey and the international literature (Golivets, 2011; Jankovska et al., 2014; Tyrväinen et al., 2003). In particular, the average values of preferences derived from the survey results were used proportionally to weight the map of traditionally managed forest with that of the SHSs.

The Analytic Hierarchy Process (AHP) was adopted to aggregate the seven indicators into a single aggregate indicator of recreational attractiveness. AHP is an efficient method for spatial multi-criteria decision analysis (Saaty, 1990; Kordi & Brandt, 2012). In addition, other studies performed AHP for the mapping of recreational suitability (Caglayan et al., 2020; Lee et al., 2010). In this study, a panel of five experts on forest planning and management was selected and involved in assigning weights to the indicators to consider all aspects related to the biophysical characteristics of ESs provided by forests. The criteria used to select the experts were the following: (Grilli et al., 2017): (i) expertise in the field of forest ESs; (ii) a deep knowledge of the Alpine forests; and (iii) no direct stake in planning and management of the study area (COF). The selected experts had the following knowledge backgrounds: two graduates in forestry with expertise in forest planning and management; one graduate in natural sciences with expertise in biodiversity conservation; one ecological economist with expertise in ESs valuation; and one graduate in social sciences with expertise in cultural services valuation. Experts were asked to compile the pairwise comparison matrix, which allowed calculating the weights to be assigned to each indicator (Table 3). The final map of recreational attractiveness was created by aggregating the seven indicators using a weighted sum.

Table 3. Weights of recreational indicators for the Cansiglio Orientale forest.

Indicator	W_i	Weight
Accommodation facilities	W_{acc}	0. 4014
Point of interests	W_{poi}	0. 2754
Paths and trails	W_{roa}	0. 1476
Grasslands	W_{pas}	0. 0907
Water elements	W_{wat}	0. 0552
Forest composition	W_{for}	0. 0296

2.2.4. Biodiversity and habitat provision

Biophysical assessment and spatial analysis

Forests are privileged places for the biodiversity conservation which, in turn, is essential for the provision of all other ESs (Brockerhoff et al., 2017). The methodology adopted for mapping the biodiversity value of the COF is explained below. In this case, five layers capable of increasing the value of biodiversity and one disturbance layer were identified as indicators. In accordance with the literature, the SHSs have been considered the elements with the highest level of biodiversity (Zapponi et al., 2014). In fact, some studies have demonstrated the positive impacts of deadwood islands on saproxylic biodiversity conservation, especially for target species such as hermit beetle (*Osmoderma eremita*), Alpine longhorn beetle (*Rosalia alpine*), *Phloeostichus denticollis* (Cateau et al., 2013; Rose & Callot, 2007).

Secondly, ecotones – i.e., transitional areas between grassland and forest – was also considered. In literature, Myster (2012) stated that ecotones have important implications for biodiversity, as well as for the provision of other ESs by the regions for which it represents the borders. In this study, a corridor of 10 m between grasslands and forests area was adopted. Regarding forest types, an increasing level of biodiversity has been considered in accordance with the literature and can be summarised as follows (Asbeck et al., 2019; Cavard et al., 2011): conifer pure forests > broadleaved pure forests > mixed forests Additionally, tree and shrub species diversity was found to be slightly higher in broadleaved forests than in conifer forests (Gao et al., 2014). Subsequently, the water elements were considered as the fourth indicator. In a recent study, Canedoli et al. (2018) found that the presence of water elements favoured species occurrence and abundance both at a landscape and local scale. In that study, a buffer zone of river corridors was considered, according to a decreasing linear fuzzy function (see Fig. 3) between 0 m and 50 m. The coefficient values of the fuzzy functions for the biodiversity and habitat provision indicators are shown in Annex 1.

Similarly to what was done for outdoor recreation, a panel of five experts assigned weights to the indicators of biodiversity and habitat provision. An AHP was performed to calculate the weight of the five indicator (Table 4) and aggregate them into a single aggregate biodiversity and habitat indicator (Saaty, 1990).

Table 4. Weights of biodiversity and habitat indicators for the Cansiglio Orientale forest.

Sub-indicator	W_i	**Weight**
SHSs	W_{shs}	0.5128
Ecotones	W_{eco}	0.2615
Grasslands	W_{pas}	0.1290
Water elements	W_{wat}	0.0634
Forest composition	W_{for}	0.0333

Human elements have been considered a phenomenon of biodiversity disturbance in accordance with the literature (Battisti et al., 2016; Piragnolo et al., 2014). In the study area, the road and path network was considered as the main factor disturbing biodiversity due to recreational activities (Marcantonio et al., 2013). However, it should be noted that the level of disturbance generated by recreational activities (e.g., walking or hiking) is rather low compared to other type of disturbances, such as fragmentation caused by different land uses (Kays et al., 2017; Marzano & Dandy, 2012). Methodologically, an increasing linear fuzzy function (see Fig. 3) between 0 m and 10 m was adopted. The threshold of 10 m was chosen since generally most visitors do not stray far from the trails. Subsequently, the biodiversity map was obtained by overlapping the biodiversity indicator map with the disturbance of paths and roads network. The indicator adopted for the biodiversity assessment is dimensionless and the values are comprised between 0 and 1.

2.2.5. Trade-offs and synergies between ESs

In the last step, a Pearson correlation analysis was performed to evaluate the spatial trade-offs and synergies between individual ESs. The Shapiro-Wilk and Anderson-Darling tests showed that the data followed a normal distribution (p=0.328 and p=0.531 respectively), so the parametric Pearson correlation test was applied. The Pearson correlation is a test that measures linear correlation between two sets of data whose values vary between −1 and 1. According to Mazziotta et al. (2022) synergies between pairs of ESs were defined as positive correlations ($r > 0$) and trade-offs as negative correlations ($r < 0$).

The results of Pearson correlation were used as a starting point for the creation of the final map. The four ESs maps were aggregated into a summary map to highlight the total value of the ESs on the site.

3. Results

3.1. Timber production

The results showed a total prescribed yield of 41,620 m^3 in the 15 years of FUMP corresponding to an average timber value equal to approximately 30.5 m^3 per unit per year. Regarding the harvested tree species, the results showed that 41% is from softwood species (17,184 m^3 of Norway spruce and silver fir) and 59% is from hardwood species (24,436 m^3 of European beech). The prescribed yield in the FUMP period highlighted values within a range between a minimum of 1,460 m^3 in year 2032 and a maximum of 3,580 m^3 in year 2031.

In addition to the prescribed yield, the silvicultural interventions implemented in the SHSs have impacted on timber production in two directions: increasing timber production in seventeen SHSs, in which the wood resulting from the opening of gaps was harvested and marketed; decreasing timber production and increasing biodiversity in four SHSs, in which the wood resulting from the opening of gaps was left for the saproxylic species. A total timber volume of approximately 2,800 m^3 (187 m^3 yr^{-1}) was harvested from the seventeen SHSs (167 m^3 per SHS), while a total timber volume of 580 m^3 (39 m^3 yr^{-1}) was transformed into lying deadwood (145 m^3 per SHS). Observing the data by tree species, the results showed that the harvested and marketed timber was represented by two thirds by European beech, by one third by conifers (17.1% of Norway spruce and 16.5% of silver fir), while the timber left on site as lying deadwood was almost exclusively European beech (93%).

For spatial analysis, the timber production in the SHSs was added to the prescribed yield value obtained for all units of the COF from the current FUMP. Figure 4 showed the final map of the timber provision for the COF after the creation of the SHSs. Observing the map, it is interesting to highlight that only two units assume a negative value in terms of provisioning services. These are the units that host an SHS in which no timber cutting is planned in the 15 years of FUMP, but where cutting interventions within the LIFE SPAN project were carried out leaving wood as deadwood on site. Moreover, more than 49% of the units have a low overall prescribed yield value (i.e., less than 50 m^3 yr^{-1}). In addition, 14% of the units have a prescribed yield value between 50 m^3 yr^{-1} and 100 m^3 yr^{-1}, while 29% between 100 m^3 yr^{-1} and 150 m^3 yr^{-1}. Only 11% of the units have a prescribed yield value greater than 150 m^3 yr^{-1}. It should be noted that the annual prescribed yield value from FUMP for COF corresponds to 4,162 m^3 yr^{-1}. As a consequence, silvicultural interventions in the SHSs resulted in an overall increase that led the annual yield of the COF to a value of 4,388 m^3 yr^{-1}.

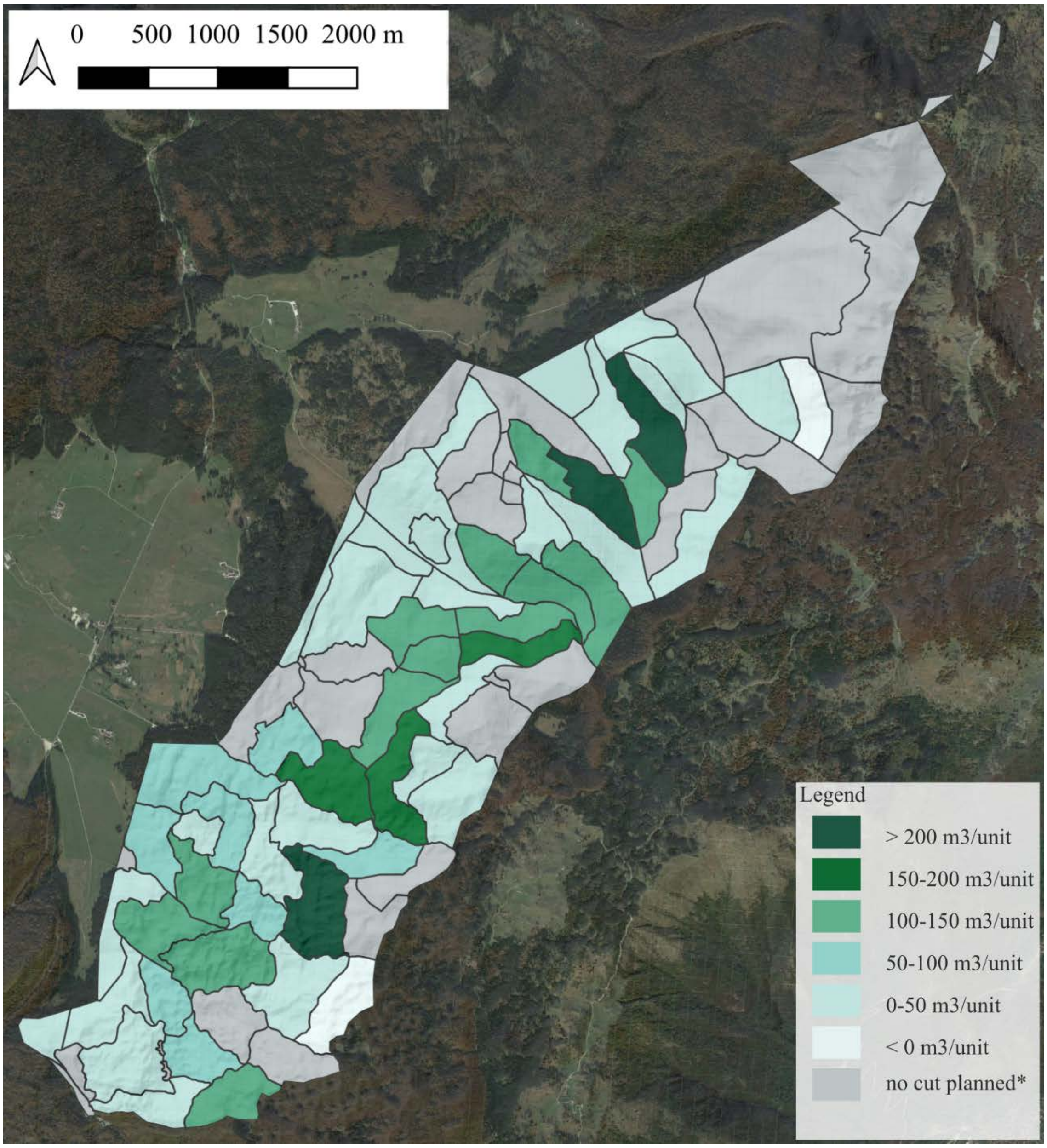

Figure 4. Map of timber provision value of the Cansiglio Orientale forest. *in grey, the units where no timber cutting is foreseen in the period considered (classes of 50 m^3/unit)

3.2. Stand stability

The results of stand stability in the COF showed an average SC value of 77.57 (SD=15.33), with a minimum of 27.74 and a maximum of 141.52. The results are distributed by stand stability class as follows: 63.1% of the forest area is in Class 1 (i.e., SC≤80, high stability); 15.3% is in Class 2 (i.e., 80<SC≤90, medium stability); 21.6% is in Class 3 (i.e., SC>90, low stability). The main descriptive statistics for the three classes are shown in Table 5. A non-normal distribution of the SC values was assessed through both the Shapiro-Wilk test and Anderson-Darling test (W=0.996, A^2=75.575, p<0.0001). Therefore, the Kruskal-Wallis non-parametric test was applied to observe whether there are statistically significant differences between the three classes of stand stability (p<0.0001).

Table 5. Descriptive statistics for the three stand stability classes based on Slenderness Coefficient in the Cansiglio Orientale forest.

Stand stability	Mean(±SD)	Median	1st quartile	3rd quartile
Class 1	71.13±13.56	70.66	61.28	80.67
Class 2	82.76±8.70	84.66	80.38	87.89
Class 3	92.20±12.24	93.82	89.39	98.63

After the creation of SHSs, the new SC values were assessed for each unit considering that gaps of approximately 0.5 ha were created by removing all the trees (see Fig. 5 black areas). The results showed that the overall stand stability of the COF has slightly improved with a decrease in the mean SC value of -0.43 (SD=0.95) included in a range from -2.73 to +0.98. In 61.9% of the units the SC value was decreased with a consequent increase in stand stability; in 38.1% of the unit the SC value has slightly increased with a consequent decrease in stand stability; in the last remaining units (5%) the SC value remained unchanged. Considering the overall SHSs areas (approximately 3.5% of total forest area), the impact of the silvicultural interventions on the stand stability of the COF as a whole is negligible. The map of the stand stability for the COF considering the silvicultural interventions in the SHSs is shown in Figure 5.

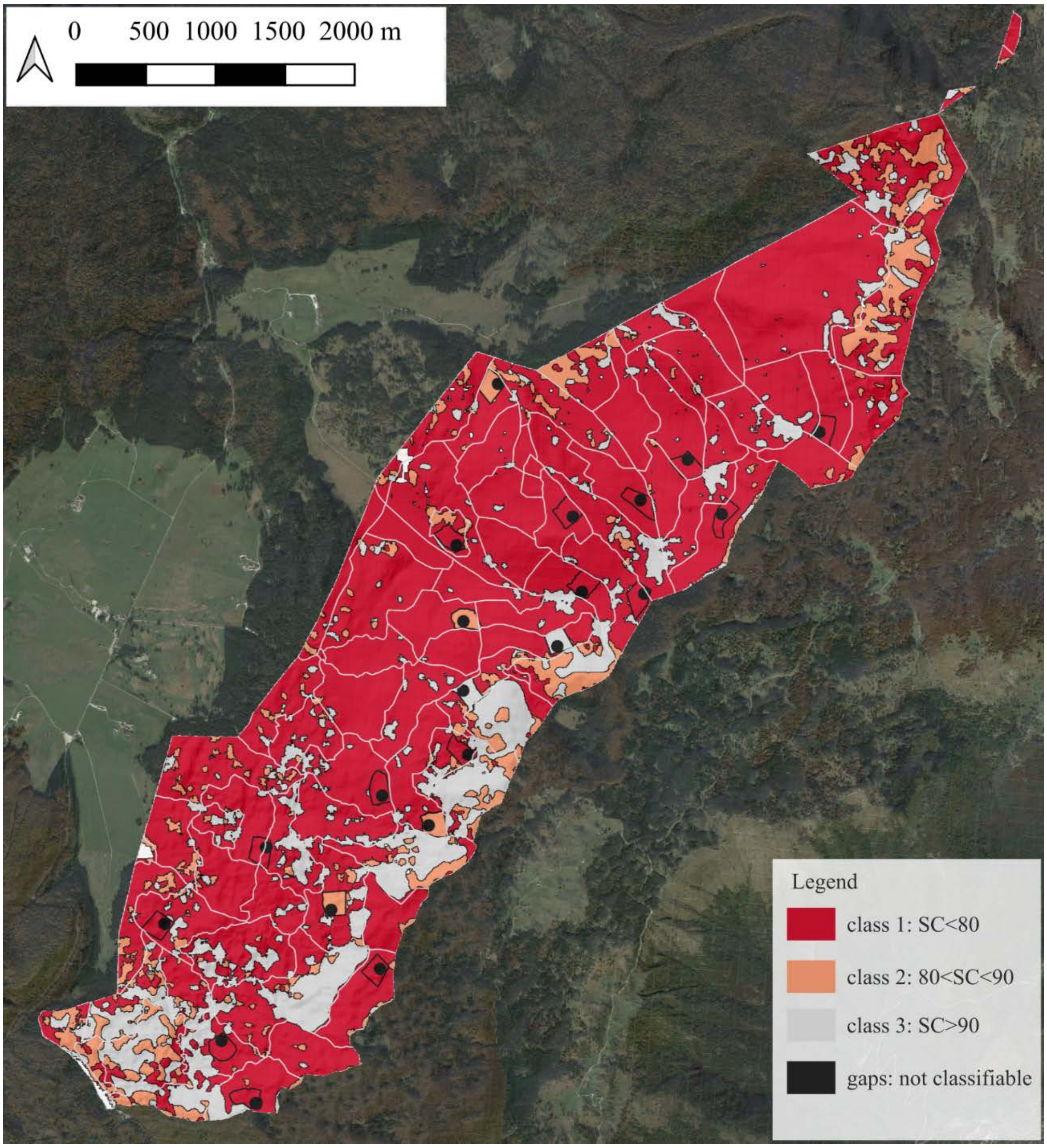

Figure 5. Stand stability map of the Cansiglio Orientale forest by classes (high stand stability in red; medium stand stability in orange; low stand stability in grey; gaps where all the trees have been cut down in black) after the realisation of the SHSs.

3.3. Outdoor recreation

The results of the questionnaire survey showed a higher visual-aesthetic preference assigned by the visitors for forest area without deadwood (mean±st.dev.: 4.43±0.84) than for forest area with high amount of deadwood (2.66±1.36). The Mann-Whitney non-parametric test showed statistical significant differences between the preferences assigned to these two photos (p<0.0001). In other terms, the managed forests are preferred by our sample of visitors to the SHSs in proportion 62:38. Therefore, a preliminary operation has been carried out to aggregate the forest indicator map with the SHSs indicator map considering the aforementioned proportion.

The map of the recreational value of the COF with the continuous values has been divided into five classes as reported in Figure 6, to facilitate the analysis of data. The first class, which represents values below 0.1, covers about 43.7% of the study area. The second (0.1-0.2) and the third class (0.2-0.3) represent a still relevant percentage of the examined territory, respectively 19.3% and 14.6%. The fourth class (0.3-0.4) is a slightly lower area (8.3%) compared to the fifth and last class (>0.4) that covers approximately 14.1% of the total forest area. In this case the difference between the three types of forests and the presence of grasslands or water elements does not particularly affect the outputs. Elements of greater influence on recreational attractiveness are accommodation facilities, points of interest and the paths and trails network. In fact, the results showed that the areas with maximum value are in correspondence of the path and trail network in proximity of an accommodation facility, while areas with minimum value are in correspondence of the pure conifer forests located in the most distant areas to accommodation facilities, points of interest, and paths and trails. In the SHSs, the recreational value tends to decrease very slightly in relation to surrounding values. Finally, the results highlighted that the mixed forests assume slightly higher recreational values than pure broadleaved and conifer forests.

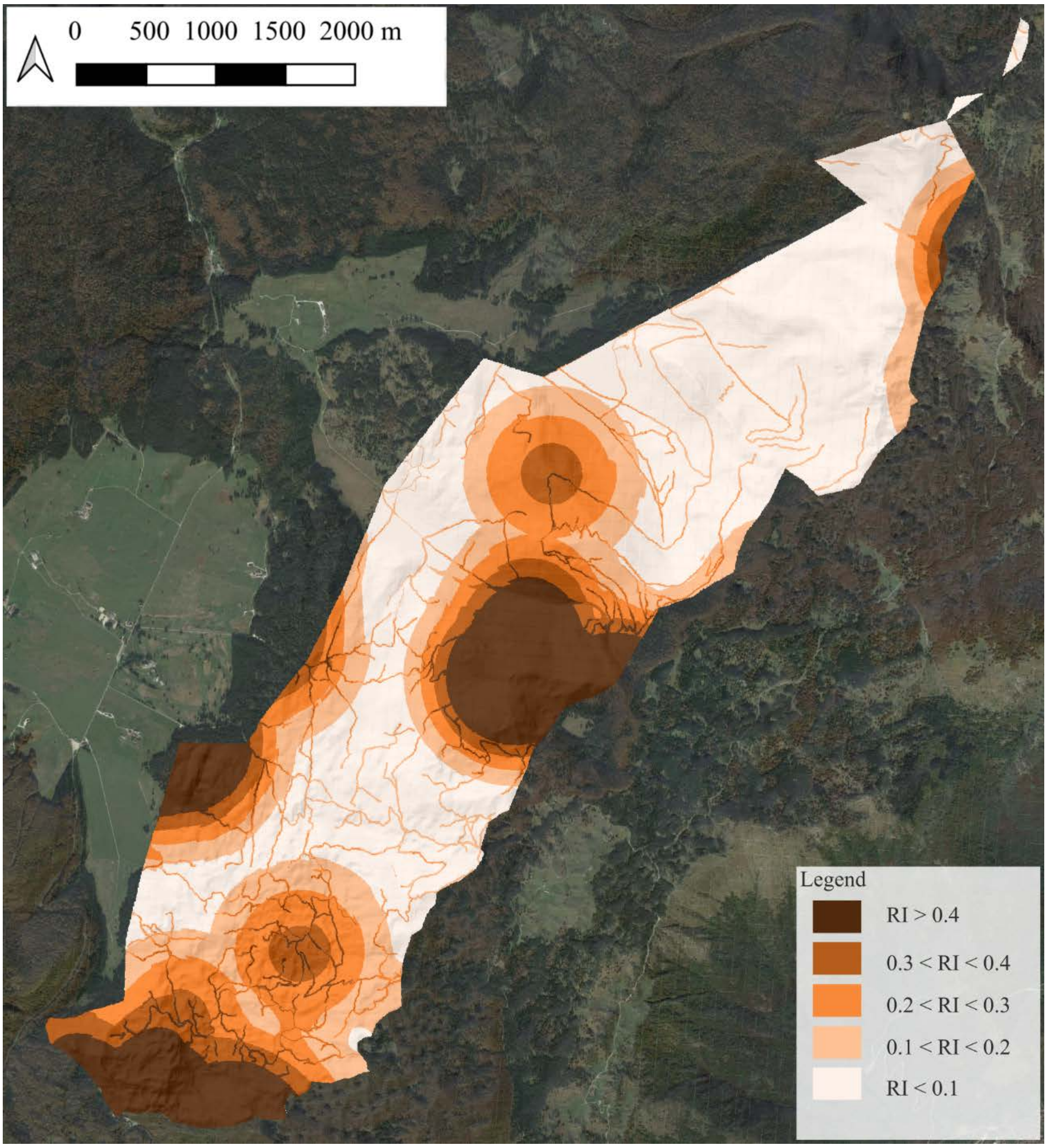

Figure 6. Map of the recreational value of the Cansiglio Orientale forest by classes within a range between 0 (minimum value) and 1 (maximum value). The recreational indicator (RI) is dimensionless.

3.4. Biodiversity and habitat provision

The results of the biodiversity and habitat provision are were mapped considering five classes included in a range between 0 and 1 as shown in Figure 7. The first class with the lowest level of biodiversity (less than 0.05) covers 46.4% of the study area in correspondence of the conifer and broadleaved forests. The second class (values between 0.05 and 0.15) includes mixed forests (49.3%) of the COF. The three classes with the highest level of biodiversity cover small portions of the study area: the third class includes grasslands and watercourses (0.7%), the fourth class includes ecotones (0.4%), while the last one the SHSs (3.2%). These results underlined the high value of biodiversity in SHSs compared to other forest areas with significantly higher biodiversity indicator (BI) values.

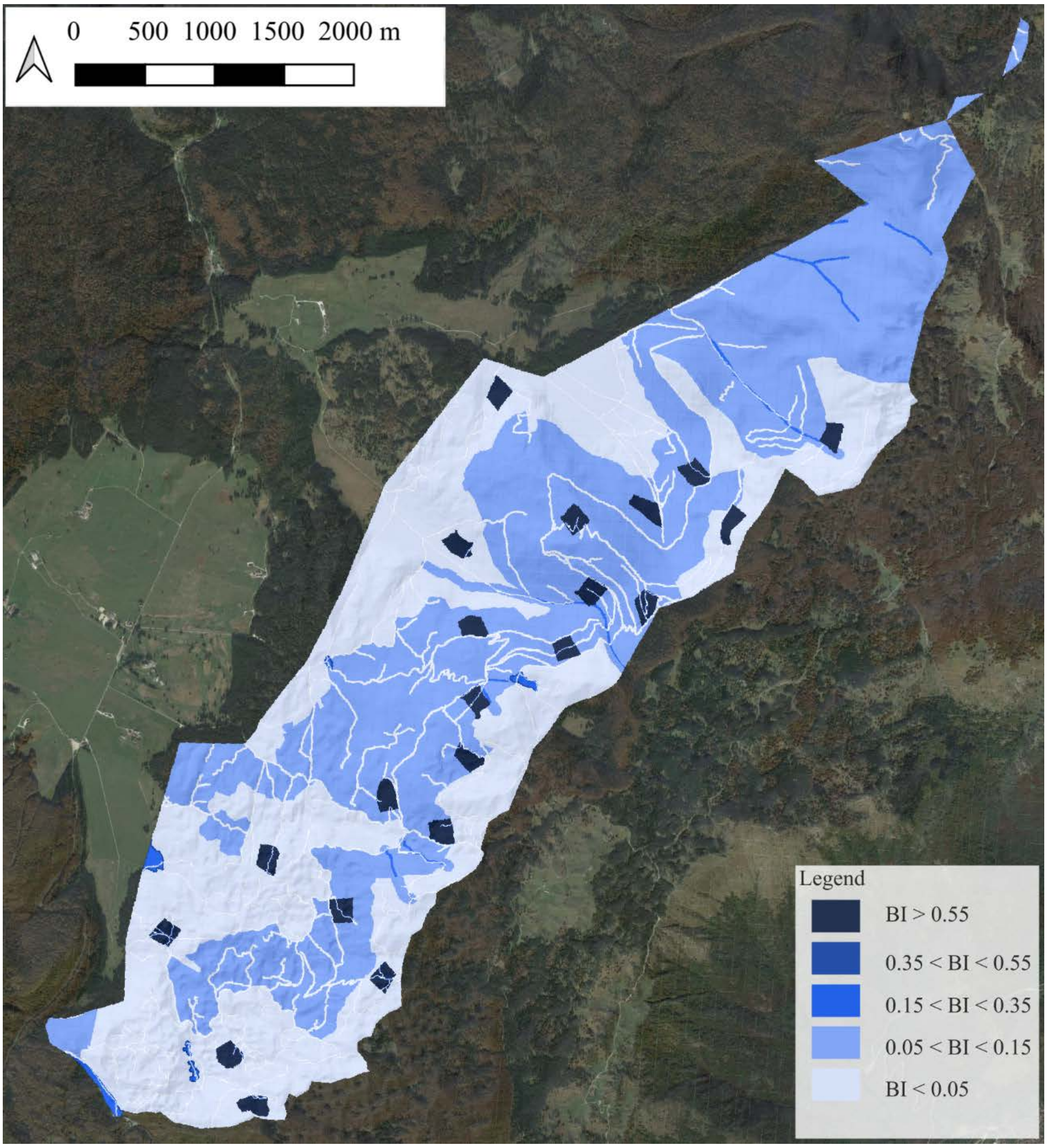

Figure 7. Map of the biodiversity value of the Cansiglio Orientale forest divided in classes within a range between 0 (minimum value) and 1 (maximum value). The biodiversity indicator (BI) is dimensionless.

3.5. Trade-offs and synergies between ESs

The results of the Pearson correlation showed a synergy between all four ESs provided by the COF. Considering all 91 forest management units (Table 6), the results highlighted a statistical significant correlation between: timber production and biodiversity conservation (r=0.473, p<0.0001); outdoor recreation and stand stability (r=0.460, p<0.0001); biodiversity conservation and stand stability (r=0.569, p<0.0001).

Table 6. Matrix of Pearson's correlation (r) between ecosystem services in the 91 forest management units of the Cansiglio Orientale forest.

	Timber provision	Stand stability	Outdoor recreation	Biodiversity conservation
Timber provision	1	0.05	0.194	0.473**
Stand stability	0.05	1	0.460**	0.569**
Outdoor recreation	0.194	0.460**	1	0.224
Biodiversity conservation	0.473**	0.569**	0.224	1

Note: *$p<0.05$; **$p<0.01$

Focusing only on SHSs (Table 7), the results showed a similar situation characterized by positive correlations between the four ESs. However, it is interesting to pointed out that in the SHSs the positive correlation between biodiversity conservation and timber production (r=0.734, p<0.001) increases as well as between timber production and stand stability (r=0.393, p=0.078). Conversely, the positive correlation between outdoor recreation and the other three ESs registered lower values compared to the other correlations.

Table 7. Matrix of Pearson's correlation (r) between ecosystem services in the 21 SHSs of the Cansiglio Orientale forest.

	Timber provision	Stand stability	Outdoor recreation	Biodiversity conservation
Timber provision	1	0.393	0.140	0.734**
Stand stability	0.393	1	0.224	0.513
Outdoor recreation	0.140	0.224	1	0.054
Biodiversity conservation	0.734**	0.513	0.054	1

Note: *$p<0.05$; **$p<0.01$

Finally, the maps of the four ESs considered were overlapped through an operation of sum. Each map has been given the same weight since the COF is managed according to the principles of forest multifunctionality and a close-to-nature approach is adopted. In other words, All ESs were given equal weight without prioritizing them. From the map of the global value (Fig. 8), expressed by a dimensionless indicator between 0 and 1. The results showed that the highest values are concentrated in correspondence with mixed forests characterized by a high recreational attractiveness or a high amounts of harvested wood. Finally, the results showed that the SHSs areas are characterized by high values mainly due to the biodiversity and habitat provision, but also secondarily to the positive impacts on other ESs.

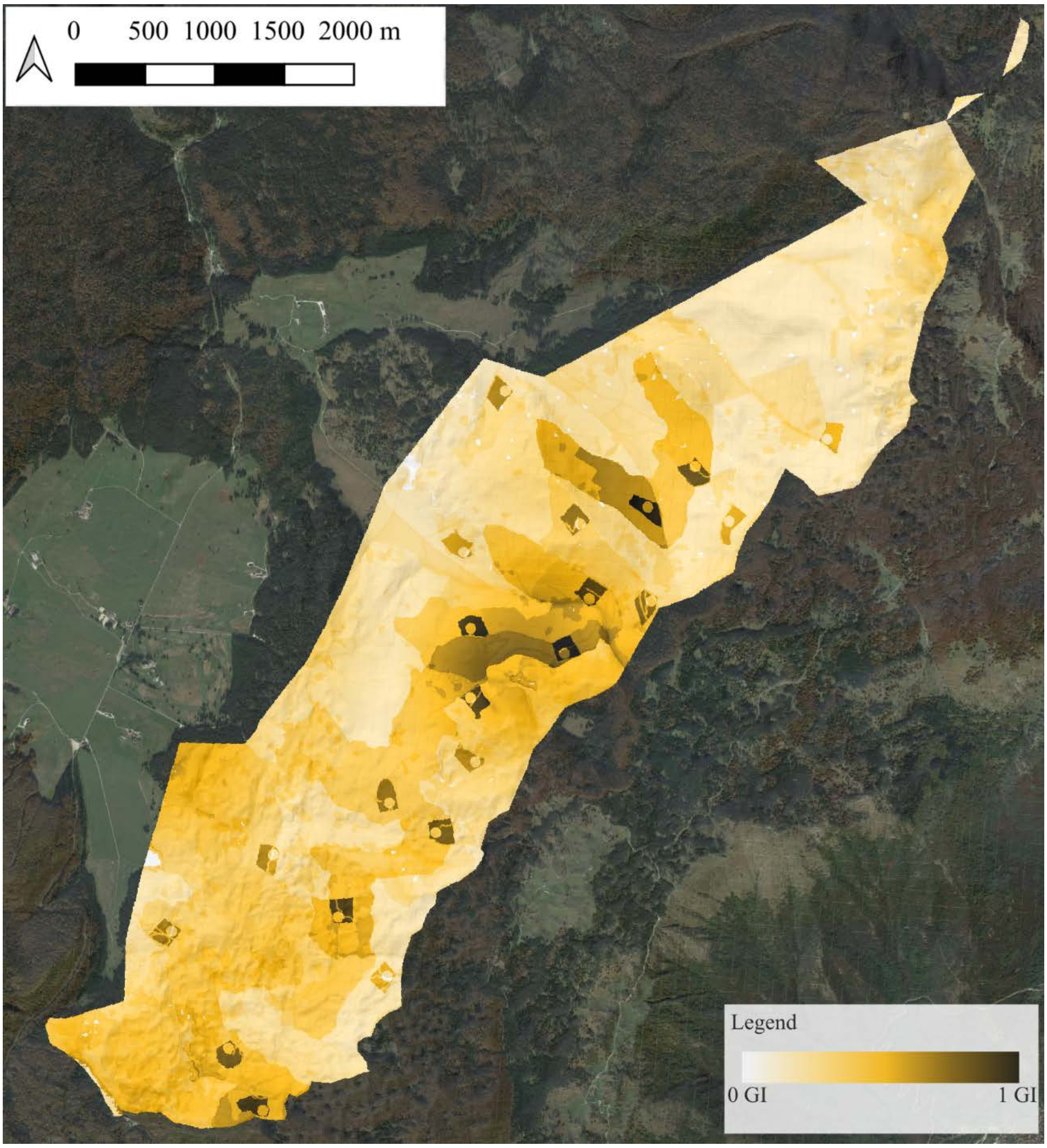

Figure 8. Map of the aggregated value of the ecosystem services provided by Cansiglio Orientale forest. The ES global indicator (GI) is dimensionless.

4. Discussion

4.1. Effects of deadwood islands on ecosystem services

The proposed method assessed and mapped the ESs provided by the SHSs within managed forests. To this end, four ESs – such as timber production, stand stability, outdoor recreation and biodiversity – were considered in an integrated manner. The results provided by this study provide a preliminary picture of the role of deadwood islands in providing ESs beyond the biodiversity and habitat provision. Furthermore, spatial allocation of ESs values and their mapping can be considered a useful tool to support decision makers in forest planning and management (Peña et al., 2015; Tiemann & Ring, 2022). As emphasized by Mazziotta et al. (2016), an aggregated map of ESs values is useful to consider the habitat requirements of multiple species and to encourage the movement of wildlife species in the ecosystem.

Regarding the management of deadwood islands in the managed forests, it is essential to assess the potential positive or negative effects on different ESs (Schwaiger et al., 2019). The effect of silvicultural interventions in SHSs – creation of microhabitat trees, lying deadwood and opening of gaps – on the provision of ESs are shown in Table 8.

Table 8. Ecosystem services supply in the SHSs of the Cansiglio Orientale forest.

ES category	ES	Δ	Description
Supporting services	Biodiversity conservation	++	Increase in saproxylic diversity due to the creation of microhabitat trees and lying deadwood and in floristic diversity due to the opening of gaps.
Provisioning services	Timber provision	+/-	Loss of area for timber production in presence of the interventions of microhabitat trees and lying deadwood creation. Increase in traded timber resulting from the opening of gaps.
Regulating services	Stand stability	-	Slight decrease in stand stability in presence of the interventions of microhabitat trees and lying

			deadwood creation. No data in the gaps
Cultural services	Outdoor recreation	+/-	Decrease in recreational attractiveness of the site due to the high amount of lying deadwood and standing microhabitat trees. Increased visual-aesthetic landscape value near the gaps.

The biodiversity value is mainly related to the tree species composition (mixed forests vs. pure conifer/broadleaved forests), age (uneven vs. even-aged), horizontal and vertical stand structure (Cavard et al., 2011). Uneven aged mixed forests are considered those with the highest biodiversity value as highlighted by many authors (Wang et al., 2019), but the presence of watercourses, ecotones, and grasslands can increase this value (Canedoli et al., 2018; Myster, 2012). However, the results of this study showed that the creation of SHSs within managed forests increases biodiversity value with special regard to the saproxylic species and floristic diversity as previously highlighted by other studies (Aerts, 2013; Mason & Zapponi, 2016). In particular, opening gaps has positive effects on biodiversity, timber provision, forest landscape diversification without compromising stand stability.

Regarding the provisioning services, the present study showed that the timber production is strictly related to the prescribed yield indicated in the FUMP as already stressed by other authors (Bont et al., 2018; Eid et al., 2002). However, the main findings also highlighted that the creation of SHSs for biodiversity conservation within the production forest led to an overall increase of the value of timber provision. This result is not in line with the international literature which highlights a trade-off between biodiversity conservation and timber production (Faith et al., 1996; Mazziotta et al., 2023; Selkimäki et al., 2020).

Regarding the deadwood islands, Mazziotta et al. (2023) found a spatial trade-off between the economic value of timber harvesting and deadwood volume in a boreal forest in Central Finland. However, Augustynczik et al. (2018) estimated that the allocation of deadwood islands in production forests leads to a very low reduction in the Net Present Value (NPV) of less than 1%. Conversely, the results of this study showed an increment in timber production due to the opening of the gaps, chosen as an intervention to increase floristic biodiversity in the SHSs. In this way, all trees removed from the gap have contributed to increase the overall value of timber supply, compensating for the loss of production area (approximately 2.5 ha for each SHS out of a total of approximately 1500 ha of forest). Therefore, timber production does not necessarily have to be in contradiction with biodiversity conservation. Opening gaps through total felling of trees inside the SHSs temporarily increases the supply of timber, but this practice is not sustainable in the long term period (Hjältén et al., 2017), while maintaining or increasing lying deadwood and standing dead trees on the site supports saproxylic species (Seibold et al., 2015). Rather, effective synergies can be achieved between timber production and biodiversity conservation when biodiversity is integrated into the broader concept of management (Biber et al., 2021; Duncker et al., 2012).

With regard to stand stability, our results highlighted that the creation of SHSs improves stand stability in over 60% of cases with a positive effect on hydrogeological protection. As emphasized by some authors, silvicultural interventions (e.g., early thinning, selective cutting) can positively influence stand stability by reducing the risk of wind and snow damage (Kerr & Haufe, 2011; Marchi et al., 2018; Cantiani & Chiavetta, 2015). In the creation of SHSs, some living trees are selected to create standing microhabitat trees, realizing basal pockets and nesting cavity on their surface, while other subjects are felled to produce lying deadwood, thus affecting stand stability. In fact, as emphasized by Zapponi et al. (2014), living trees selected as microhabitat trees have diameter at breast height between 40 and 75 cm that could also contributed effectively to the stand stability. However, it should be noted that opening large gaps within SHSs could have the effect of increasing windthrow risk in accordance with the current literature (Drăgoi & Barnoaiea, 2018).

Regarding the cultural services, this study showed that the highest outdoor recreational value is in areas where there are accommodation facilities and points of interest (e.g., panoramic points, natural and historical landmarks) and more widely along the paths and in proximity of grasslands. In literature, other studies have emphasized that the recreational attractiveness of forests is strictly related to the amenities available at the site as-well-as the biophysical context (Lingua et al., 2023). More precisely, Ciesielski and Stereńczak (2018) found that the recreational attractiveness is influenced by accessibility of forest area, forest appearance (e.g., tree species composition, age, stand structure), forest management condition (e.g., leisure infrastructure), and factors disturbing forest perception (e.g., noise, litter, too many visitors). Ziernicka-Wojtaszek and Malec (2022) stressed that recreational attractiveness is not only related to the infrastructure but also to the aesthetics of the surrounding landscape. Besides, the target of visitors to a site, with their attitudes (e.g., activities carried out) and aesthetic preferences, can play a key role in choosing the most frequented areas. In this sense, the main findings of this study demonstrated that the outdoor recreational value increases in mixed forests compared to pure conifer and broadleaved forests and slightly decreases in proximity to the SHSs. The latter is due to the lower visitors' aesthetic preferences for landscapes characterized by a high amount of deadwood (within the SHSs) compared to forest areas without deadwood. In fact, the outcomes of the questionnaire survey highlighted a clear preference for the managed forests compared to the landscape of the SHSs. These results are in line with the international literature, which highlights people's preferences for mixed forests compared to pure conifer and broadleaved forests (Grilli et al., 2014) as-well-as for forests characterized by a low or no amount of deadwood (Golivets, 2011; Tyrväinen et al., 2003). However, the loss of outdoor recreational value in SHSs is negligible due to the small size (approximately 2.5 ha) and spatial distribution of deadwood islands throughout the forest.

4.2. Management recommendations

The positive effects on biodiversity conservation are the key aspect of creating a network of SHSs in managed forests. The effects are widely documented in the international literature and considered an effective biodiversity conservation strategy (Cateau et al., 2013; Mason & Zapponi, 2016; Rose & Callot, 2007). However, the creation of SHSs may have an impact on other ESs that must be considered in order to mitigate negative effects and enhance synergistic effects.

Timber production is potentially in conflict with biodiversity conservation as emphasized by some authors (Sedmák et al., 2020; Ciesielski et al., 2024). However, the results of this study highlighted that in the SHSs this trade-off is partially offset by the sale of additional wood obtained from opening the gaps. From a practical point of view, the choice of where to locate SHSs is of key importance to avoid conflicts between timber production and biodiversity conservation. In these senses, forest areas with an high stumpage value and located near forest roads should be avoided, preferring marginal areas.

The creation of SHSs within managed forests could have potential negative effects on stand stability due to the opening gaps and creating microhabitat trees. As highlighted by Ciesielski et al. (2024), trade-offs incur in mountain forests where canopy cover prevents soil erosion, landslides and other hydrogeological disasters. Based on these considerations, the creation of SHSs must be done following some precautions First of all, the opening of the gaps should not exceed 0.1-0.2 ha in order not to increase the windthrow risk related to the margin effect (Gadow, 2000) and fragmentation (Holeksa et al., 2017). Secondly, the choice of living trees to produce lying deadwood and standing microhabitat trees should be made considering the slenderness coefficient (SC) of the individual trees, in order not to raise excessively the overall stand slenderness value.

Regarding outdoor recreation, our results showed that the high amount of microhabitat trees, lying deadwood and standing dead trees within the SHSs is perceived negatively by visitors. Other studies found that European visitors aesthetically prefer forests with little deadwood to those with a high amount of deadwood (Jankovska et al., 2014; Pastorella et al., 2016; Paletto et al., 2023a), while Notaro et al. (2019) found that the opening of gaps in forest cover has a potential positive effect on the aesthetics of the forest landscape in the eyes of visitors. As highlighted by Paletto et al. (2023b), the negative perception of visitors is mainly due to a low level of knowledge of the relationship between deadwood and biodiversity conservation. In practice, it is desirable that forest managers inform visitors about the role and importance of deadwood and SHSs in order to raise social awareness. Lee et al. (2010) found that there is a wide variety of strategies to captivate visitors, making them more aware of the issues of biodiversity, which could contribute to increase the preference for high biodiversity areas such as SHSs. However, it is important to underline that the loss of recreational value within the SHSs is negligible at a landscape scale, because other aspects play a more key role in the recreational attractiveness of a site (i.e. accommodation facilities and points of interest).

To further reduce the potential impacts of SHSs on recreational attractiveness, it could be useful to locate these areas away from accommodation facilities, points of interest, paths and trails. Alternatively, a potential valorisation of the SHSs could be to reconnect the nodal points of the recreational service by transforming the SHSs into new points of interest. To do this, information panels, notice boards and deviations from the original trails could be created to allow privileged views for visitors to appreciate the high level of biodiversity of the area.

Finally, we can assert that interventions to create SHSs in managed forests have overall positive effects, firstly on biodiversity and secondly on other ESs, provided that some key measures are adopted such as: (i) realization of SHSs away from paths and roads network and in areas that are not visible to visitors; (ii) opening of gaps in SHSs with area less than 0.2 ha to reduce the risk of soil erosion and natural hazards (landslides and storms); (iii) select microhabitat trees over trees with lower timber value so as not to compromise stumpage value; (iv) avoid the creation of lying deadwood in forests at risk from biotic threats (e.g., Norway spruce forests affected by the bark beetle).

5. Conclusions

In the present study was to implement a methodology capable of analysing in an integrated manner the effects of the creation of SHSs on different ESs was implemented in accordance with the forest management strategies adopted. In particular, geospatial analysis tools appear to be useful to provide valuable results to decision makers of forest areas. The consequent results can be used to select the areas within the managed forests in which to create the SHSs. The key principles for the identification of SHSs can be summarized as follows: (i) select marginal areas from a logistical/economic point of view, in order not to compromise the timber production; (ii) prefer areas with a low slenderness coefficient, in order not to increase the windthrow and snow risk; (iii) choose areas far from points of interest and path network, in order not to reduce the recreational attractiveness of the site.

From a methodological point of view, the main strengths were considering the impacts of SHS creation on multiple ESs and spatially representing the value of ESs to support forest managers and planners in future choices. Conversely, one of the main weaknesses is having considered only the slenderness coefficient as a proxy for stand stability, while other variables were not included in our study such as tree species composition, crown length and form, root anchorage, vertical stand structure. A second weakness is related to the analysis of trade-offs and synergies that has been based only on the positive or negative correlation between ESs in pairs.

Future insights can be developed on the use of this methodology at different scales (e.g. regional or national) and for different types of values (e.g. monetary values). However, the most important result observed appears to be the possibility of promoting the conservation of forest biodiversity and at the same time not to compromise the provision of other ESs, through the adoption of the right analysis tools that can lead to the most effective management choices.

References

Abildtrup J., Garcia S., Olsen S.B., & Stenger A., 2013, Spatial preference heterogeneity in forest recreation. Ecological Economics, 92, 67–77. https://doi.org/10.1016/j.ecolecon.2013.01.001

Adeyemi A.A., & Adesoye P.O., 2016, Tree Slenderness Coefficient and Percent Canopy Cover in Oban Group Forest , Nigeria Tree Slenderness Coefficient and Percent Canopy Cover in Oban. Journal of Natural Sciences Research, 6(4), 9–17.

Aerts R., 2013, Old Trees: Extraction, Conservation Can Coexist. Science, 339, 904–904.

Akujärvi A., Repo A., Akujärvi A.M., Liski J., 2021, Bridging mapping and simulation modelling in the ecosystem service assessments of boreal forests: effects of bioenergy production on carbon dynamics. Forest Ecosystems, 8, 4. https://doi.org/10.1186/s40663-021-00283-2

Ament J.M., Moore C.A., Herbst M., & Cumming G.S., 2017, Cultural Ecosystem Services in Protected Areas: Understanding Bundles, Trade-Offs, and Synergies. Conservation Letters 10, 440–450. https://doi.org/10.1111/conl.12283

Asbeck T., Pyttel P., Frey J., & Bauhus J., 2019, Predicting abundance and diversity of tree-related microhabitats in Central European montane forests from common forest attributes. Forest Ecology and Management, 432, 400–408. https://doi.org/10.1016/j.foreco.2018.09.043

Augustynczik A.L.D., Yousefpour R., Rodriguez L.C.E., & Hanewinkel M., 2018, Conservation Costs of Retention Forestry and Optimal Habitat Network Selection in Southwestern Germany. Ecological Economics, 148, 92–102. https://doi.org/10.1016/j.ecolecon.2018.02.013

Bachofen H., & Zingg A., 2001, Effectiveness of structure improvement thinning on stand structure in subalpine Norway spruce (Picea abies (L.) Karst.) stands. Forest Ecology and Management, 145, 137–149. https://doi.org/10.1016/S0378-1127(00)00581-8

Bayraktar S., Becagli C., & Paletto A., 2024, Young Generations' Perception of Deadwood in Forest Landscapes: Insights from Turkish Students. South-East European Forestry, 15, 187–200. https://doi.org/10.15177/seefor.24-15

Bayraktar S., Paletto A., & Floris A., 2020. Deadwood volume and quality in recreational forests: the case study of the Belgrade forest (Turkey). Forest Systems 29(2), 1–13. https://doi.org/10.5424/fs/2020292-16560

Bayraktar S., Sefidi K., & Paletto A., 2025, Perceptions of deadwood among Iranian university students. International Forestry Review, 27, 296–316. https://doi.org/10.1505/146554825840319582

Baskent E.Z., Borges J.G., Kašpar J., & Tahri M., 2020, A design for addressing multiple ecosystem services in forest management planning. Forests, 11, 1–24. https://doi.org/10.3390/f11101108

Battisti C., Poeta G., & Fanelli G., 2016, An Introduction to Disturbance Ecology. A Road Map for Wildlife Management and Conservation, Environmental Science and Engineering (Subseries: Environmental Science). Springer, Switzerland. https://doi.org/10.1007/978-3-319-32476-0_6

Bengtsson J., Bullock J.M., Egoh B., Everson C., Everson T., O'Connor T., O'Farrell P.J., Smith H.G., & Lindborg R., 2019, Grasslands—more important for ecosystem services than you might think. Ecosphere, 10. https://doi.org/10.1002/ecs2.2582

Biber P., Schwaiger F., Poschenrieder W., & Pretzsch H., 2021, A fuzzy logic-based approach for evaluating forest ecosystem service provision and biodiversity applied to a case study landscape in Southern Germany. European Journal of Forest Research, 140, 1559–1586. https://doi.org/10.1007/s10342-021-01418-4

Biber P., Felton A., Nieuwenhuis M., Lindbladh M., Black K., Bahýl J., Bingöl Ö., Borges J.G., Botequim B., Brukas V., Bugalho M.N., Corradini G., Eriksson L.O., Forsell N., Hengeveld G.M., Hoogstra-Klein M.A., Kadıoğullar A.I., Karahalil U., Lodin I., Lundholm A., Makrickienė E., Masiero M., Mozgeris G., Pivoriūnas N., Poschenrieder W., Pretzsch H., Sedmák R., & Tuček J., 2020, Forest Biodiversity, Carbon Sequestration, and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes Across Europe. Frontiers in Ecology and Evolution, 8. https://doi.org/10.3389/fevo.2020.547696

Bont L. G., Fraefel M., & Fischer C., 2018, A spatially explicit method to assess the economic suitability of a forest road network for timber harvest in steep terrain. Forests, 9, 1–21. https://doi.org/10.3390/f9040169

Brockerhoff E.G., Barbaro L., Castagneyrol B., Forrester D.I., Gardiner B., González-Olabarria J.R., Lyver P.O.B., Meurisse N., Oxbrough A., Taki H., Thompson I.D., van der Plas F., & Jactel H., 2017, Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodiversity and Conservation, 26, 3005–3035. https://doi.org/10.1007/s10531-017-1453-2

Caglayan İ., Yeşil A., Cieszewski C., Gül F.K., & Kabak Ö., 2020, Mapping of recreation suitability in the Belgrad Forest Stands. Applied Geography, 116. https://doi.org/10.1016/j.apgeog.2020.102153

Canedoli C., Manenti R., & Padoa-Schioppa E., 2018, Birds biodiversity in urban and periurban forests: environmental determinants at local and landscape scales. Urban Ecosystems, 21, 779–793. https://doi.org/10.1007/s11252-018-0757-7

Cantiani P., & Chiavetta U., 2015, Estimating the mechanical stability of Pinus nigra arn. Using an alternative approach across several plantations in central Italy. IForest, 8, 846–852. https://doi.org/10.3832/ifor1300-007

Cateau E., Parrot M., Roux A., Reyna K., Rossi M., Bruciamacchie M., & Vallauri D., 2013, Réseau d'îlots de vieux bois: Eléments de méthode et test dans les forêts publiques du Mont-Ventoux.

WWF Rapport, Paris.
Cavard X., Macdonald S.E., Bergeron Y., & Chen H.Y.H., 2011, Importance of mixedwoods for biodiversity conservation: Evidence for understory plants, songbirds, soil fauna, and ectomycorrhizae in northern forests. Environmental Reviews, 19, 142–161. https://doi.org/10.1139/A11-004
Ciesielski M., & Stereńczak K., 2018, What do we expect from forests? The European view of public demands. Journal of Environmental Management, 209, 139–151. https://doi.org/10.1016/j.jenvman.2017.12.032
Ciesielski M., Gołos P., Wysocka-Fijorek M., & Kaliszewski A., 2024, Relationships between forest ecosystem services – current state of knowledge. Folia Forestali Polonica, 66, 228–248. https://doi.org/0.2478/ffp-2024-001
De Groot R.S., Wilson M.A., & Boumans R.M.J., 2002, A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics, 41, 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7
De Meo I., Cantiani M.G., Ferretti F., & Paletto A., 2018, Qualitative assessment of forest ecosystem services: The stakeholders' point of view in support of landscape planning. Forests, 9, 1–16. https://doi.org/10.3390/f9080465
De Meo I., Paletto A., & Cantiani M.G., 2015, The attractiveness of forests: Preferences and perceptions in a mountain community in Italy. Annals of Forest Research, 58, 145–156. https://doi.org/10.15287/afr.2015.308
Dorren L.K.A., Berger F., Imeson A.C., Maier B., & Rey F., 2004, Integrity, stability and management of protection forests in the European Alps. Forest Ecology and Management, 195, 165–176. https://doi.org/10.1016/j.foreco.2004.02.057
Drăgoi M., & Barnoaiea I., 2018, Accounting for windthrow risk in forest management planning: a Romanian tailor-made solution Marian. Forest Systems, 27.
Duncker P.S., Raulund-Rasmussen K., Gundersen P., Katzensteiner K., De Jong J., Ravn H.P., Smith M., Eckmüllner O., & Spiecker H., 2012, How forest management affects ecosystem services, including timber production and economic return: Synergies and trade-offs. Ecology & Society, 17. https://doi.org/10.5751/ES-05066-170450
EC, 2023, Guidance on the Development of Public and Private Payment Schemes for Forest Ecosystem Service. Brussels: European Commission.
EC, 2021, New EU Forest Strategy for 2030. Brussels: European Commission.
Ehrlich P.R., & Ehrlich A.H., 1981, Extinction: The Causes and Consequences of the Disappearance of Species. Random House Inc, New York.
Eid T., Fredrik Hoen H., & Økseter P., 2002, Timber production possibilities of the Norwegian forest area and measures for a sustainable forestry. Forest Policy and Economics, 4, 187–200. https://doi.org/10.1016/S1389-9341(01)00069-7
Faith D.P., Walker P.A., Ive J.R., & Belbin L., 1996, Integrating conservation and forestry production: exploring trade-offs between biodiversity and production in regional land-use assessment. Forest Ecology and Management, 85, 251–260.
Gadow K., 2000, Evaluating risk in forest planning models. Silva Fennica, 34. https://doi.org/10.14214/sf.639
Gao T., Hedblom M., Emilsson T., & Nielsen A.B., 2014, The role of forest stand structure as biodiversity indicator. Forest Ecology and Management, 330, 82–93. https://doi.org/10.1016/j.foreco.2014.07.007
Gardiner B.A., Stagey G.R., Belcher R.E., & Wood C.J., 1997, Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. Forestry, 70, 233–252. https://doi.org/10.1093/forestry/70.3.233
Garrido P., Elbakidze M., & Angelstam P., 2017, Stakeholders' perceptions on ecosystem services in Östergötland's (Sweden) threatened oak wood-pasture landscapes. Landscape and Urban Planning, 158, 96–104. https://doi.org/10.1016/j.landurbplan.2016.08.018
Gasparini P., & Tabacchi G., 2011, L'Inventario Nazionale delle Foreste e dei serbatoi forestali di Carbonio INFC 2005. Secondo inventario forestale nazionale italiano. Metodi e risultati. Edagricole, Milano.
Ge Y., Chen H., Zhang M., & Li X., 2022. Area Threshold Interval of Urban Forest Patches Required

to Maintain the Synergy between Biodiversity Conservation and Recreational Services: Case Study in Beijing, China. Forests, 13, 1848. https://doi.org/10.3390/f13111848

Golivets M., 2011, Aesthetic Values of Forest Landscapes. Master Thesis, Swedish University of Agricultural Sciences, Alnarp.

Grilli G., De Meo I., Garegnani G., & Paletto A., 2017, A multi-criteria framework to assess the sustainability of renewable energy development in the Alps. Journal of Environmental Planning and Management, 60, 1276–1295. http://dx.doi.org/10.1080/09640568.2016.1216398

Grilli G., Paletto A., & De Meo I., 2014, Economic valuation of forest recreation in an alpine valley. Baltic Forestry, 20, 167–175.

Hagemann U., Moroni M.T., & Makeschin F., 2009, Deadwood abundance in Labrador high-boreal black spruce forests. Canadian Journal of Forest Research, 39, 131–142. https://doi.org/10.1139/X08-166

Herold A., & Ulmer U., 2001, Stand stability in the Swiss National Forest Inventory: Assessment technique, reproducibility and relevance. Forest Ecology and Management, 145, 29–42. https://doi.org/10.1016/S0378-1127(00)00572-7

Herrero C., Monleon V.J., Gómez N., & Bravo F., 2016, Distribution of dead wood volume and mass in Mediterranean *Fagus sylvatica* L. forests in Northern Iberian Peninsula. Implications for field sampling inventory. Forest Systems, 25(3), e069. https://doi.org/ https://doi.org/10.5424/fs/2016253-09009

Hjältén J., Hägglund R., Löfroth T., Roberge J.M., Dynesius M., & Olsson J., 2017, Forest restoration by burning and gap cutting of voluntary set-asides yield distinct immediate effects on saproxylic beetles. Biodiversity and Conservation, 26, 1623–1640. https://doi.org/10.1007/s10531-017-1321-0

Holeksa J., Jaloviar P., Kucbel S., Saniga M., Svoboda M., Szewczyk J., Szwagrzyk J., Zielonka T., & Żywiec M., 2017, Models of disturbance driven dynamics in the West Carpathian spruce forests. Forest Ecology and Management, 388, 79–89. https://doi.org/10.1016/j.foreco.2016.08.026

Jankovska I., Straupe I., Brumelis G., Donis J., & Kupfere L., 2014, Urban forests of Riga, Latvia - pressures, naturalness, attitudes and management. Baltic Forestry, 20, 342–351.

Kays R., Parsons A.W., Baker M.C., Kalies E.L., Forrester T., Costello R., Rota C.T., Millspaugh J.J., & McShea W.J., 2017, Does hunting or hiking affect wildlife communities in protected areas? Journal of Applied Ecology, 54, 242–252. https://doi.org/10.1111/1365-2664.12700

Kerr G., & Haufe J., 2011, Thinning practice. A Silvicultural Guide, Edinburgh. ed.

Kordi M., & Brandt S.A., 2012, Effects of increasing fuzziness on analytic hierarchy process for spatial multicriteria decision analysis. Computers, Environment and Urban Systems, 36, 43–53. https://doi.org/10.1016/j.compenvurbsys.2011.07.004

Krsnik G., Reynolds K.M., Murphy P., Paplanus S., Garcia-Gonzalo J., & González Olabarria J.R., 2023, Forest use suitability: Towards decision-making-oriented sustainable management of forest ecosystem services. Geography and Sustainability, 4, 414–427. https://doi.org/10.1016/j.geosus.2023.09.002

Lachat T., & Bütler R., 2008, Îlots de sénescence et arbres-habitat pour augmenter la biodiversité en forêt. La Forêt, 6, 20–21.

Lassauce A., Paillet Y., Jactel H., & Bouget C., 2011, Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecological Indicators 11(5), 1027–1039. https://doi.org/10.1016/j.ecolind.2011.02.004

Lee C.F., Huang H.I., & Yeh H.R., 2010, Developing an evaluation model for destination attractiveness: Sustainable forest recreation tourism in Taiwan. Journal of Sustainable Tourism, 18, 811–828. https://doi.org/10.1080/09669581003690478

Lingua F., Coops N.C., & Griess V.C., 2023, Assessing forest recreational potential from social media data and remote sensing technologies data. Ecological Indicators, 149, 110165. https://doi.org/10.1016/j.ecolind.2023.110165

Lombardi F., & Mali B., 2016, Deadwood as a driver of forest functions. Italian Journal of Agronomy 11(1), 23–26. https://doi.org/10.1016/S1125-4718(24)00464-X

Lončarić D., Prodan M.P., & Dlačić J., 2021, Memorable tourism experiences inspired by the beauty of nature. Tourism and Hospitality Management, 27, 315–337.

https://doi.org/10.20867/THM.27.2.5
Malczewski J., 1999, GIS and multi-criteria decision analysis. 1st ed. New York: J. Wiley & Sons.
Maes J., Egoh B., Willemen L., Liquete C., Vihervaara P., Schägner J.P., Grizzetti B., Drakou E.G., La Notte A., Zulian G., Bouraoui F., Luisa Paracchini M., Braat L., & Bidoglio G., 2012, Mapping ecosystem services for policy support and decision making in the European Union. Ecosystem Services, 1, 31–39. https://doi.org/10.1016/j.ecoser.2012.06.004
Maes J., Hauck J., Paracchini M.L., Ratamäki O., Hutchins M., Termansen M., Furman E., Pérez-Soba M., Braat L., & Bidoglio G., 2013, Mainstreaming ecosystem services into EU policy. Current Opinion in Environmental Sustainability, 5, 128–134. https://doi.org/10.1016/j.cosust.2013.01.002
Maes J., Teller A., Erhard M., Condé S., Vallecillo S., Barredo J.I., Paracchini M.L., Abdul Malak D., Trombetti M., Vigiak O., Zulian G., Addamo A.M., Grizzetti B., Somma F., Hagyo A., Vogt P., Polce C., Jones A., Marin A.I., Ivits E., Mauri A., Rega C., Czúcz B., Ceccherini G., Pisoni E., Ceglar A., De Palma P., Cerrani I., Meroni M., Caudullo G., Lugato E., Vogt J.V., Spinoni J., Cammalleri C., Bastrup-Birk A., San Miguel J., San Román S., Kristensen P., Christiansen T., Zal N., de Roo A., Cardoso A.C., Pistocchi A., Del Barrio Alvarellos I., Tsiamis K., Gervasini E., Deriu I., La Notte A., Abad Viñas R., Vizzarri M., Camia A., Robert N., Kakoulaki G., Garcia Bendito E., Panagos P., Ballabio C., Scarpa S., Montanarella L., Orgiazzi A., Fernandez Ugalde O., & Santos-Martín F., 2020, Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment, EUR 30161 EN, Publications Office of the European Union, Ispra, 2020. ISBN 978-92-76-17833-0, doi:10.2760/757183, JRC120383.
Marcantonio M., Rocchini D., Geri F., Bacaro G., Amici V., 2013, Biodiversity, roads, & landscape fragmentation: Two Mediterranean cases. Applied Geography, 42, 63–72. https://doi.org/10.1016/j.apgeog.2013.05.001
Marchi M., Paletto A., Cantiani P., Bianchetto E., & de Meo I., 2018, Comparing thinning system effects on ecosystem services provision in artificial black pine (Pinus nigra J. F. Arnold) Forests. Forests, 9, 1–16. https://doi.org/10.3390/f9040188
Marzano M., & Dandy N., 2012, Recreationist behaviour in forests and the disturbance of wildlife. Biodiversity and Conservation, 21, 2967–2986. https://doi.org/10.1007/s10531-012-0350-y
Marzetti S., Disegna M., Villani G., & Speranza M., 2011, Conservation and recreational values from semi-natural grasslands for visitors to two italian parks. Journal of Environmental Planning and Management, 54, 169–191. https://doi.org/10.1080/09640568.2010.505792
Mason F., & Zapponi L., 2016, The forest biodiversity artery: Towards forest management for saproxylic conservation. IForest, 9, 205–216. https://doi.org/10.3832/ifor1657-008
Mazziotta A., Borges P., Kangas A., Halme P., & Eyvindson K., 2023, Spatial trade-offs between ecological and economical sustainability in the boreal production forest. Journal of Environmental Management, 330, 117144. https://doi.org/10.1016/j.jenvman.2022.117144
Mazziotta A., Heilmann-Clausen J., Bruun H.H., Fritz Ö., Aude E., & Tøttrup A.P., 2016, Restoring hydrology and old-growth structures in a former production forest: Modelling the long-term effects on biodiversity. Forest Ecology and Management, 381, 125–133. https://doi.org/10.1016/j.foreco.2016.09.028
Mazziotta A., Lundström J., Forsell N., Moor H., Eggers J., Subramanian N., Aquilué N., Morán-Ordóñez A., Brotons L., & Snäll T., 2022, More future synergies and less trade-offs between forest ecosystem services with natural climate solutions instead of bioeconomy solutions. Global Change Biology, 28, 6333–6348. https://doi.org/10.1111/gcb.16364
MEA, 2005, Millenium Ecosystem Assessment (MA). In Ecosystems and Human Well-Being: Synthesis. Island Press: Washington, DC, USA.
Müller A., Olschewski R., Unterberger C., & Knoke T., 2020, The valuation of forest ecosystem services as a tool for management planning – A choice experiment. Journal of Environmental Management, 271, 111008. https://doi.org/10.1016/j.jenvman.2020.111008
Myster R.W., 2012, Ecotones between forest and grassland, Ecotones Between Forest and Grassland. Springer Science & Business Media, New York. https://doi.org/10.1007/978-1-4614-3797-0
Notaro S., Grilli G., & Paletto A., 2019, The Role of Emotions on Tourists' Willingness to Pay for the Alpine Landscape: a Latent Class Approach. Landscape Research, 44, 743–756. https://doi.org/https://doi.org/10.1080/01426397.2018.1513129

Obiang Ndong G., Therond O., & Cousin I., 2020, Analysis of relationships between ecosystem services: A generic classification and review of the literature. Ecosystem Services, 43, 101120. https://doi.org/10.1016/j.ecoser.2020.101120

Paletto A., Bayraktar S., Becagli C., & De Meo I., 2023a, Young Generations' Perception of the Role of Deadwood in Forests: Comparison between Italy and Türkiye. Ecologies, 4, 426–441. https://doi.org/10.3390/ecologies4020027

Paletto A., Cantiani M.G., & De Meo I., 2015a, Public Participation in Forest Landscape Management Planning (FLMP) in Italy. Journal of Sustainable Forestry, 34, 465–482. https://doi.org/10.1080/10549811.2015.1026447

Paletto A., De Meo I., Grilli G., & Notaro S., 2023b, Valuing nature-based recreation in forest areas in Italy: An application of Travel Cost Method (TCM). Journal of Leisure Research, 54, 26–45. https://doi.org/10.1080/00222216.2022.2115328

Paletto A., De Meo I., Cantiani P., & Ferretti F., 2014, Effects of forest management on the amount of deadwood in Mediterranean oak ecosystems. Annals of Forest Science 71, 791–800. https://doi.org/10.1007/s13595-014-0377-1

Paletto A., Geitner C., Grilli G., Hastik R., Pastorella F., & Garcìa L.R., 2015b, Mapping the value of ecosystem services: A case study from the Austrian Alps. Annals of Forest Research, 58, 157–175. https://doi.org/10.15287/afr.2015.335

Pastorella F., Giacovelli G., De Meo I., & Paletto A., 2017, People's preferences for Alpine forest landscapes: Results of an internet-based survey. Journal of Forest Research, 22, 36–43. https://doi.org/10.1080/13416979.2017.1279708

Pastorella, F., Avdagić, A., Čabaravdić, A., Mraković, A., Osmanović, M., & Paletto, A., 2016, Tourists' perception of deadwood in mountain forests. Annals of Forest Research, 59, 311–326. https://doi.org/10.15287/afr.2016.482.

Peña L., Casado-Arzuaga I., & Onaindia M., 2015, Mapping recreation supply and demand using an ecological and a social evaluation approach. Ecosystem Services, 13, 108–118. https://doi.org/10.1016/j.ecoser.2014.12.008

Phelps J., Jones C.A., Pendergrass J.A., & Gómez-Baggethun E., 2015, Environmental liability: A missing use for ecosystem services valuation. Proc. Natl. Acad. Sci. U. S. A., 112, E5370. https://doi.org/10.1073/pnas.1514893112

Piragnolo M., Pirotti F., Guarnieri A., Vettore A., & Salogni G., 2014, Geo-spatial support for assessment of anthropic impact on biodiversity. ISPRS International Journal of Geo-Information, 3, 599–618. https://doi.org/10.3390/ijgi3020599

Riccioli F., Fratini R., Fagarazzi C., Cozzi M., Viccaro M., Romano S., Rocchini D., Diaz S.E., & Tattoni C., 2020, Mapping the recreational value of coppices' management systems in Tuscany. Sustainability, 12, 1–18. https://doi.org/10.3390/su12198039

Rose O., & Callot H., 2007, Redécouverte de Phloeostichus denticollis Redtenbacher, 1842 dans le massif des Vosges (France) (Coleoptera, Phloeostichidae). L'Entomologiste, 63, 129–133.

Saaty T.L., 1990, How to make a decision: The Analytic Hierarchy Process. European Journal of Operational Research, 48, 9–26. https://doi.org/10.1007/978-1-4614-3597-6_1

Sacher P., Meyerhoff J., & Mayer M., 2022, Evidence of the association between deadwood and forest recreational site choices. Forest Policy and Economics, 135, 102638. https://doi.org/10.1016/j.forpol.2021.102638

Schägner J.P., Brander L., Maes J., & Hartje V., 2013, Mapping ecosystem services' values: Current practice and future prospects. Ecosystem Services, 4, 33–46. https://doi.org/10.1016/j.ecoser.2013.02.003

Schelhaas M.J., Kramer K., Peltola H., van der Werf D.C., Wijdeven S.M.J., 2007, Introducing tree interactions in wind damage simulation. Ecological Modelling, 207, 197–209. https://doi.org/10.1016/j.ecolmodel.2007.04.025

Schwaiger F., Poschenrieder W., Biber P., & Pretzsch H., 2019, Ecosystem service trade-offs for adaptive forest management. Ecosystem Services, 39, 100993. https://doi.org/10.1016/j.ecoser.2019.100993

Schwenk W.S., Donovan T.M., Keeton W.S., & Nunery J.S., 2012, Carbon storage, timber production, and biodiversity: Comparing ecosystem services with multi-criteria decision analysis. Ecological Applications, 22, 1612–1627. https://doi.org/10.1890/11-0864.1

Sedmák, R. et al., 2020, Optimizing the tending of forest stands with interactive decision maps to balance the financial incomes and ecological risks according to owner demands: case study in Rakovník, the Czech Republic. Forests, 11, 730. https://doi.org/10.3390/f11070730
Seibold S., Bässler C., Brandl R., Gossner M.M., Thorn S., Ulyshen M.D., & Müller J., 2015, Experimental studies of dead-wood biodiversity - A review identifying global gaps in knowledge. Biological Conservation, 191, 139–149. https://doi.org/10.1016/j.biocon.2015.06.006
Selkimäki M., González-Olabarria J.R., Trasobares A., & Pukkala T., 2020, Trade-offs between economic profitability, erosion risk mitigation and biodiversity in the management of uneven-aged Abies alba Mill. stands. Annals of Forest Science, 77. https://doi.org/10.1007/s13595-019-0914-z
Sergiacomi C., Floris A., Clementel F., & Paletto A., 2024, The economic value of the protective functions of mountain forests: A case study in the Italian Alps. Journal of Susainable Forestry 43, 153–173. https://doi.org/10.1080/10549811.2025.2451438
Sergiacomi C., & Paletto A., 2025, Mapping the monetary value of forest-based recreation: a case study in the Italian Carnic Prealps. Annals of Forest Research, 68, 85–101. https://doi.org/10.15287/afr.2025.3515
Sergiacomi C., Vuletić D., Paletto A., & Fagarazzi C., 2022, Exploring tourist Preferences on the Visitor Management System: the Case Study of Plitvice Lakes National Park. South-east European Forestry, 13, 67–77. https://doi.org/10.3390/f13050717
Skłodowski J., Gołos P., Skłodowski M., & Ożga W., 2013, The preferences of visitors to selected forest areas for tourism and recreational purposes. The Forest Research Papers, 74, 293–305. https://doi.org/10.2478/frp-2013-0028
Skrzyszewski J., & Pach M., 2020, The use of the slenderness coefficient in diagnosing wind damage risks. Acta Silvestria LVII, 7–24. https://doi.org/10.15576/actasilvestria/2020.lvii.7
Šmudla R., 2004, Utilisation of mathematical models and growth simulators for creating forest management plans and planning the tending felling. Journal of Forest Science, 50, 374–381. https://doi.org/10.17221/4664-jfs
TEEB, 2010, The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations.
Termansen M., McClean C.J., & Jensen F.S., 2013, Modelling and mapping spatial heterogeneity in forest recreation services. Ecological Economics, 92, 48–57. https://doi.org/10.1016/j.ecolecon.2013.05.001
Thrippleton T., Temperli C., Krumm F., Mey R., Zell J., Stroheker S., Gossner M.M., Bebi P., Thürig E., & Schweier J., 2023, Balancing disturbance risk and ecosystem service provisioning in Swiss mountain forests: an increasing challenge under climate change. Regional Environmental Change, 23, 29. https://doi.org/10.1007/s10113-022-02015-w
Tiemann A., & Ring I., 2022, Towards ecosystem service assessment: Developing biophysical indicators for forest ecosystem services. Ecolological Indicators, 137. https://doi.org/10.1016/j.ecolind.2022.108704
Tyrväinen L., Silvennoinen H., & Kolehmainen O., 2003, Can ecological and aesthetic values be combined in urban forest management? Urban Forestry & Urban Greening, 1, 135–149. https://doi.org/https://doi.org/10.1078/1618-8667-00014
Vacchiano G., Berretti R., Mondino E.B., Meloni F., & Motta R., 2016, Assessing the effect of disturbances on the functionality of direct protection forests. Mountain Research and Development, 36, 41–55. https://doi.org/10.1659/MRD-JOURNAL-D-15-00075.1
Wang X., Hua F., Wang L., Wilcove D.S., & Yu D.W., 2019, The biodiversity benefit of native forests and mixed-species plantations over monoculture plantations. Diversity and Distributions, 25, 1721–1735. https://doi.org/10.1111/ddi.12972
Zadeh L.A., 1965, Fuzzy Sets. Infection Control, 8, 338–353.
Zapponi L., Minari E., Longo L., Toni I., Mason F., & Campanaro A., 2014, The Habitat-Trees experiment: using exotic tree species as new microhabitats for the native fauna. IForest, 8, 464–470. https://doi.org/10.3832/ifor1281-007
Ziernicka-Wojtaszek A., & Malec M., 2022, Evaluating Local Attractiveness for Tourism and Recreation—A Case Study of the Communes in Brzeski County, Poland. Land, 11. https://doi.org/10.3390/land11010039

ANNEX 1

Coefficient values of the fuzzy functions for the recreational and biodiversity indicators for the Cansiglio Orientale forest.

	Parameters of the membership functions			
	a (m)	b (m)	c (m)	d (m)
Recreational indicators				
Points of interest	0	1000	-	-
Paths and trails network	-	-	0	10
Water elements	-	-	0	20
Biodiversity and habitat provision indicators				
Water elements	-	-	0	50
Paths and trails network	-	-	0	10