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Comparing forest ecosystem services in two protected areas: insights from Stelvio National Park and Orobie Bergamasche Regional Park (Italy)

Abstract: Filippelli E., Cresi L., Diolaiuti G.A., Senese A., *Comparing forest ecosystem services in two protected areas: insights from Stelvio National Park and Orobie Bergamasche Regional Park (Italy)*. (IT ISSN 0391-9838, 2025). Forests play a crucial role in supporting biodiversity, mitigating climate change, and protecting human settlements from natural hazards. Ecosystem services (ESs, defined as the benefits that nature provides and that contribute to environmental stability and the well-being of the socioeconomic system) provided by forested areas include tangible benefits (e.g. timber production), and intangible functions (e.g. carbon sequestration and landslide hazard reduction). Quantifying the economic value of these services is essential to integrate environmental benefits into policy and land management decisions. In this study, we compare the economic value of these three key forest ecosystem services across two protected areas in Northern Italy: the Lombardy sector of the Stelvio National Park (LSNP) and the Orobie Bergamasche Regional Park (ORBP). We find that ORBP provides higher annual economic value for both timber production (1.46 million €/year) and carbon sequestration (3.38 million €/year), while LSNP offers slightly greater per-hectare carbon sequestration value (1,174 €/year/km²) and marginally higher landslide hazard reduction (€388,779 vs. €370,980). These results reveal that forest composition and management practices strongly influence the services provided. For instance, mountain pine forests maximize carbon sequestration, while larch-dominated stands achieve higher timber prices but lower sequestration rates. Our findings align with previous research emphasizing the trade-offs and synergies between provisioning and regulating services, particularly in Alpine contexts. The study contributes to growing efforts to economically evaluate natural capital, especially in mountainous regions where ecosystem services are critical yet undervalued. By focusing on two parks within the same bioclimatic region but with different topographic and administrative features, this work illustrates how spatial context shapes ecosystem value. This comparative analysis underscores the importance of tailoring forest management strategies to local conditions and service priorities. It also provides a useful reference for regional planning and climate adaptation policies in Alpine areas and beyond.

Key words: Alpine forest, Forest Ecosystem Services, Timber production, Carbon sequestration, Landslide hazard reduction, Economic valuation, Italian Alps.

Riassunto: Filippelli E., Cresi L., Diolaiuti G.A., Senese A., *Confronto dei servizi ecosistemici forestali in due aree protette: esempi tratti dal Parco Nazionale dello Stelvio e dal Parco Regionale delle Orobie Bergamasche (Italia)*. (IT ISSN 0391-9838, 2025). Le foreste svolgono un ruolo cruciale nel sostenere la biodiversità, nel mitigare i cambiamenti climatici e nel proteggere gli insediamenti umani dai rischi naturali. I servizi ecosistemici (ES) sono definiti come i benefici che la natura fornisce e che contribuiscono alla stabilità ambientale e al benessere del sistema socioeconomico, essi includono benefici tangibili, come la produzione di legname, e funzioni intangibili, come il sequestro del carbonio e la riduzione del rischio di frane. Quantificare il valore economico di questi servizi è essenziale per integrare i benefici ambientali nelle politiche e nelle decisioni di gestione del territorio. In questo studio, abbiamo confrontato il valore economico di questi tre servizi ecosistemici forestali chiave in due aree protette del Nord Italia: il settore lombardo del Parco Nazionale dello Stelvio (LSNP) e il Parco Regionale delle Orobie Bergamasche (ORBP). I risultati ottenuti indicano che il Parco Regionale delle Orobie Bergamasche fornisce un valore economico annuale più elevato sia per la produzione di legname (1.46 milioni di €/anno), sia per il sequestro di carbonio (3.38 milioni di €/anno), mentre il LSNP offre un valore di sequestro di carbonio per ettaro leggermente superiore (1174 €/anno/km²) e una riduzione della pericolosità da frana leggermente superiore (388 779 € contro 370 980 €). Questi risultati rivelano che la composizione delle foreste e le pratiche di gestione applicate influenzano fortemente i servizi forniti. Ad esempio, le foreste di pino mugo massimizzano il sequestro di carbonio, mentre i boschi dominati dai larici ottengono prezzi del legname più elevati, ma con tassi di sequestro di carbonio inferiori. I nostri risultati sono in linea con le ricerche precedenti che sottolineano le sinergie tra i servizi di fornitura e di regolazione, in particolare nei contesti alpini. Questo studio contribuisce alle ricerche per valutare il capitale naturale dal punto di vista economico, soprattutto nelle regioni montane, dove i servizi ecosistemici sono fondamentali. Concentrandosi su due parchi all'interno della stessa regione bioclimatica, ma con caratteristiche topografiche e amministrative diverse, questo lavoro mostra come il contesto spaziale influenzi in modo significativo il valore degli ecosistemi. Questa analisi comparativa evidenzia l'importanza di adattare le strategie di gestione forestale alle condizioni locali e alle priorità dei servizi. Fornisce, inoltre, un utile riferimento per la pianificazione regionale e le politiche di adattamento al clima nelle aree alpine e limitrofe.

Termini chiave: Foreste alpine, Servizi ecosistemici forestali, Produzione di legname, Stoccaggio di carbonio, Riduzione della pericolosità franosa, Valutazione economica, Alpi italiane.

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INTRODUCTION

The Ecosystems services (ESs) are defined as the benefits that nature provides and that contribute to environmental stability and the well-being of the socioeconomic system (Daily, 1997). The first notion of ESs dates back to the late 1970s (Westman, 1977; Ehrlich and Ehrlich, 1981), and the first systematic definition and classification was published in 2005 by the Millennium Ecosystem Assessment (2005). Since then, the number of publications on ESs has grown exponentially (Fisher *et al.*, 2009). The classification of ESs underwent diverse interpretations and changes through the last decades, and among those, consensus has been reached by the Millennium Ecosystem Assessment (2005) and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young, 2018). This latter divides ESs in three main categories: i) provisioning (i.e. products obtained from ecosystems), ii) regulation and maintenance (i.e. provide the regulation of ecosystem processes), and iii) cultural (i.e. non-material benefits provided by the ecosystem to the people). Over the past decades, the concept of ecosystem services has become central to environmental sciences, as it helps highlight the essential functions that natural ecosystems provide in supporting human well-being (Costanza *et al.*, 1997; Millennium Ecosystem Assessment, 2005). Despite their importance, many of these services remain undervalued or unaccounted for in economic and land-use decision-making processes (Buckley, 2011). Consequently, their economic value needs to be recognized and made explicit. A variety of valuation methods have been developed to estimate the economic value of ESs, including market-based approaches, cost-based methods (e.g., replacement cost, avoided damage cost), and preference-based techniques such as contingent valuation and choice modeling (de Groot *et al.*, 2012; Pascual *et al.*, 2012).

Forests offer a wide array of ecosystem services, including provisioning (e.g. raw material), regulating (e.g. water regulation), and cultural services (e.g. outdoor recreational activities) (Costanza *et al.*, 1997; Sayre *et al.*, 2018; Senese *et al.*, 2023). In mountainous areas, such as in the Alpine region, forest ecosystems play a critical role not only in providing renewable resources but also in regulating natural hazards and contributing to carbon balance (Baral *et al.*, 2017). These services are of strategic importance in the context of climate change adaptation and environmental hazard reduction (Munang *et al.*, 2013). Finally, mountain forests harbor a rich biodiversity (Hassan *et al.*, 2005).

In this study, we aim to compare the role of forests in providing ESs in two Italian protected areas, framing timber production, carbon sequestration and landslide hazard reduction. Timber is a direct-use service whose monetary worth is observable through market stumpage prices (Costanza *et al.*, 1997). Carbon sequestration is a

regulating service that can be priced indirectly (e.g. via voluntary-market credits, EU-ETS benchmarks or the social cost of carbon) while also carrying option value for future climate policy (Costanza *et al.*, 1997). Landslide hazard reduction is likewise an indirect-use service whose value is estimated through avoided-damage or replacement-cost models (Costanza *et al.*, 1997). In this study, we refer to landslide hazard rather than risk, as the analysis focuses on the physical susceptibility of slopes and forest mitigation effects, without incorporating exposure or vulnerability components. Residual option and non-use components (e.g. society's willingness to conserve protective forests beyond current markets) are best captured through contingent or participatory valuation, completing the economic picture for these otherwise incomparable Alpine parks.

By quantifying and comparing the monetary value of these three ecosystem services, the research intends to support sustainable forest management and inform regional planning and climate adaptation policies.

In Italy, the Stelvio National Park and the Orobic Bergamasche Regional Park represent two emblematic examples of the interaction between natural ecosystems and human activities. These parks form an ideal paired study area because they occupy the same Central-Alpine climatic belt, sit only 120 km apart, and are governed by the same regional policies on forest, climate and risk management (yet they differ sharply in reduction status, elevation span, settlement density and forest structure). This contrast provides a natural experiment: it isolates how legal mandates and socio-economic context modulate the monetary value of identical ecosystem functions (i.e. timber supply, carbon uptake and slope-stability), while holding constant biogeographic setting and data availability. Because the two areas jointly drain into the Po Basin, the results speak directly to Lombardy's climate-adaptation and environmental hazard-reduction strategies, giving the comparison both scientific rigor and immediate policy relevance.

STUDY AREA

The study area includes two protected areas within the Lombardy Region (Northern Italy): the Lombardy sector of the Stelvio National Park and the Orobic Bergamasche Regional Park (fig. 1).

The Stelvio National Park was established in 1935; it is one of Europe's most significant protected areas, located in the Central Alps across Lombardy, Trentino, and South Tyrol. It covers the four provinces of Trento, Bolzano, Brescia and Sondrio and its 134,620 hectares make it the largest Italian park. It encompasses the Ortles-Cevedale massif, featuring glaciers, alpine forests, and vast

green pastures. In this area, several Sites of Community Importance (92/43/EEC Directive) are recognized as well as Special Areas of Conservation (D'Agata *et al.*, 2014; Boggero *et al.*, 2019). Our research is focused on the Lombardy sector of the park (LSNP) that covers an area of 598 km² (ranging from 962 m a.s.l. to 3774 m a.s.l.). Forest ecosystems of different composition and structure cover 129.73 km², about 22% of the total area (data from webpage of the IIT Lombardy region, see <https://www.geoportale.regione.lombardia.it>).

With an area of 699.05 km², the Orobie Bergamasche Regional Park (OBRP) is the largest of the regional parks in Lombardy with high naturalness, having been established relatively recently (LR 15/09/1989 n. 56, see also Giupponi and Giorgi, 2017). It is located further south than the Lombardy sector of the Stelvio National Park and ranges from 487 m a.s.l. to 3035 m a.s.l. Forest ecosystems cover 46% of the total park area (320.26 km²).

Despite sharing the same regional climate and overarching reduction regime, the two parks exhibit complementary forest structures (fig. 2): OBRP's mix is characteristic of mid-elevation, commercially managed forests (i.e. spruce, beech and fir), whereas LSNP's stands reflect high-elevation, protective forests dominated by larch and mountain pine. Both parks maintain small relics of broadleaved and minor conifer types, underscoring their ecological heterogeneity, but their quantitative divergence in dominant species underscores fundamentally different silvicultural histories, altitudinal belts and management objectives.

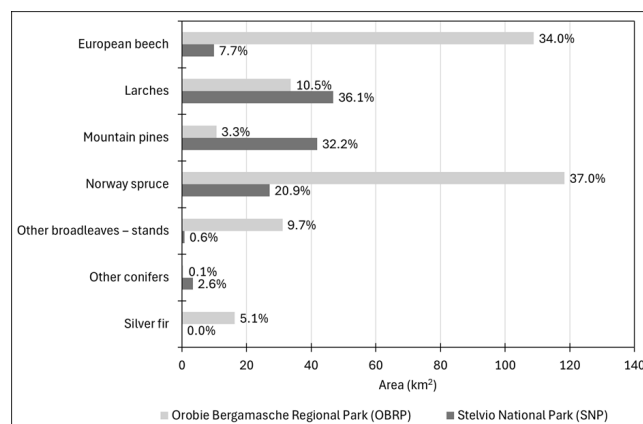


Figure 2 - Relative composition of seven main forest categories (in alpha-betic order) in the Orobie Bergamasche Regional Park (OBRP, light grey bars) and the Lombardy sector of the Stelvio National Park (LSNP, dark grey bars), expressed both as percentage of total forest cover (labels) and as area (km² on the x-axis).

METHODS

Timber production

Timber production is considered a final service (Haines-Young and Potschin-Young, 2018), because it is one of the outcomes of ecosystems (natural, semi-natural or highly modified) that most directly influence human well-being. Timber production services result in tangible goods (i.e. items that have value to people). Consequently, timber production is regulated by a market and therefore has a definite monetary value. To estimate its economic value on

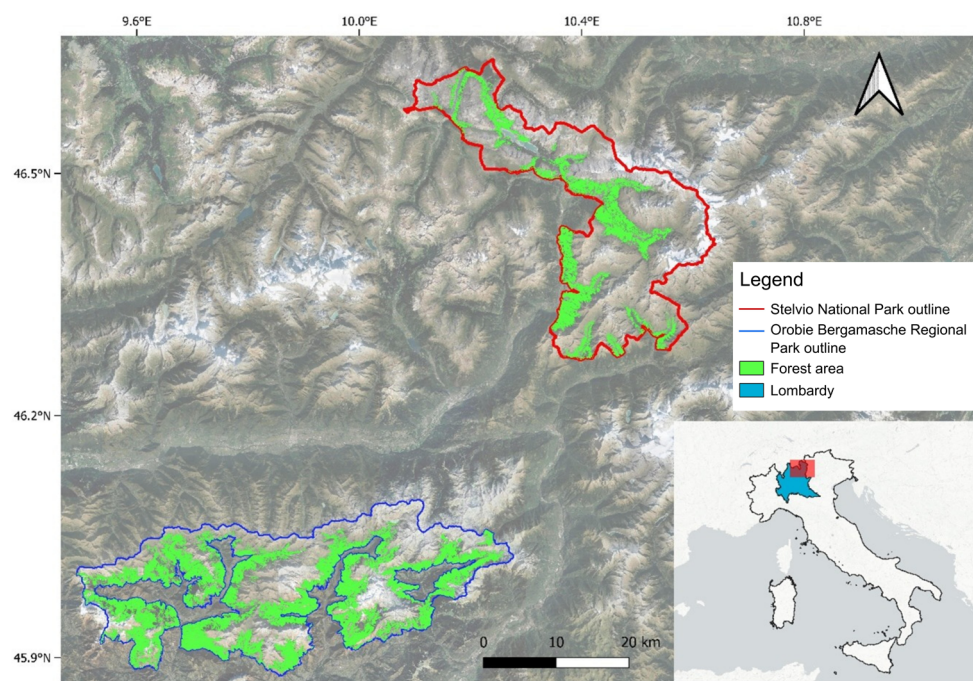


Figure 1 - Study area including the Lombardy sector of the Stelvio National Park (LSNP, red outline) and the Orobie Bergamasche Regional Park (OBRP, blue outline). Park outlines (in red and blue) and forest areas (in green) are derived from data in the webpage of the IIT Lombardy region (<https://www.geoportale.regione.lombardia.it>).

a yearly basis in the parks (V_{TP} , €/year), we followed the approach proposed by Grilli *et al.* (2015):

$$V_{TP} = V \times TP \quad (1)$$

where V indicates the volume of timber that has been cut annually ($m^3/year$), and TP is the average price of timber (€/m³). For both parks, the annual values of V are available in the webpage of the IIT Lombardy region (<https://www.geoportale.regione.lombardia.it>). We then computed the mean of these annual values across the observation period and quantified the associated uncertainty by calculating the 95% confidence interval using the t-distribution. The standard error of the mean was derived from the sample standard deviation and the number of years in the time series. The data available actually go from 2011 to 2023 (fig. 3). These datasets are provided by the Lombardy Forest Cut Information System (SITaB - Sistema Informativo dei Tagli Forestali). All forestry operations are subject to notification.

As a market price reference for timber stocks, we used price tags from www.legnotrentino.it, which reports the average price for each quarter since 2006. Specifically, we used two different types of prices (i.e. standing and roadside timber), as we have no information on the type of sales for the two parks. As reported in the Legnotrentino web page, in the case of standing sales (i.e. the timber is still in the forest) the price is based on pre-cutting estimates. The prices for roadside sales (i.e. the timber has already been cut and is ready for transport), on the other hand, are generally higher as they include the labor costs of preparation. Therefore, the inclusion of the roadside timber price allows the costs associated with harvesting to be included in the calculation. However, both prices (i.e. standing and roadside timber) could exclude the costs associated with silvicultural treatments required to reach the level of timber production and the values of non-use and existence. As the cut timber volumes range from 2011 to 2023 (fig. 3), we considered the same timeframe for timber prices (fig. 4).

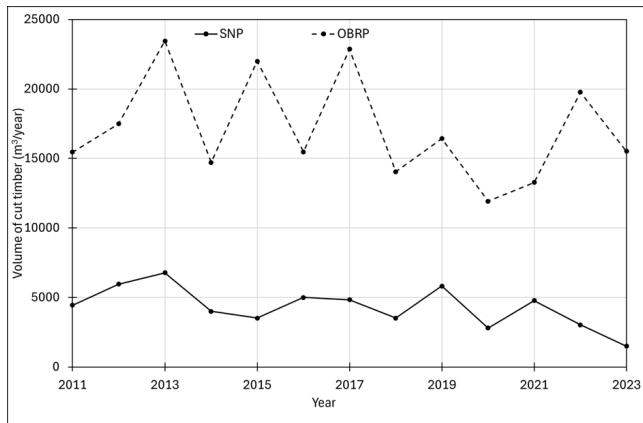


Figure 3 - Annual cumulative volume values of timber that has been cut annually for both parks (i.e. LSNP-Lombardy sector of the Stelvio National Park and OBRP - Orobic Bergamasche Regional Park) from 2011 to 2023.

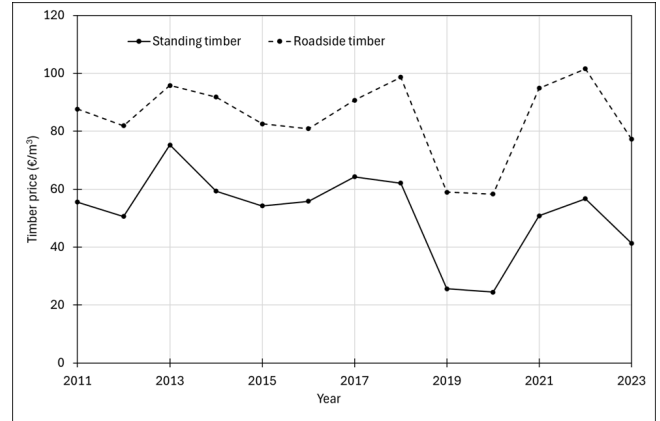


Figure 4 - Annual mean timber price values from 2011 to 2023 referred to the two different types (i.e. standing and roadside). Data from Legnotrentino portal.

Carbon sequestration

Carbon sequestration is considered an ecosystem function in the group V5.1 - “Atmospheric composition and conditions” (Haines-Young and Potschin-Young, 2018). In Haines-Young and Potschin-Young (2018), “Regulation of the chemical composition of the atmosphere” is distinguished from “Regulation of temperature and humidity, including ventilation and transpiration”. With this differentiation, the former includes the regulation of greenhouse gases (and not just CO₂) on a global scale, while the latter considers services on a more local scale, but not exclusively. However, carbon sequestration can be used as a proxy measure of the regulatory effect that the ecosystem may have with respect to an important constituent of the atmosphere (Haines-Young and Potschin-Young, 2018).

In the context of carbon sequestration, biomass plays a crucial role as a natural carbon sink, primarily categorized into aboveground biomass (AGB) and belowground biomass (BGB). AGB refers to the living organic matter found above the soil surface, including stems, branches, and leaves. Conversely, BGB encompasses the living organic matter below the soil surface, predominantly composed of roots. The forest carbon pools were assessed according to Penman *et al.* (2003). In this study, to estimate the economic value of carbon sequestration (V_{CS} , €/year) we considered living carbon in terms of above and below ground biomass (AGB and BGB, respectively, both in t/year). To assess the biomass values for the studied areas, we followed the methodologies adopted in the carbon sequestration evaluations performed in other studies conducted in the Italian Alps (Grilli *et al.*, 2015; Barbagallo *et al.*, 2024). According with these studies, we calculated the economic value of carbon sequestration ES adopting the following formula:

$$V_{cs} = [(AGB + BGB) \times CC] \times P_C \quad (2)$$

where CC is the carbon content coefficient, assumed to be equal to 0.5 across forest types (Sollins *et al.*, 1987; Coomes *et al.*, 2002), and P_c is the average carbon price in the voluntary carbon market (4.59 €/t, related to 2012, Peters-Stanley *et al.*, 2013). To be able to compare the results from the two parks, the valuations were standardized and adjusted to the same carbon content and carbon price (Nolander and Lundmark, 2024).

We quantified the cumulative AGB and BGB using the following formulas:

$$AGB = \sum_i^N I_i \times BEF_i \times WBD_i \times A_i \quad (3)$$

$$BGB = \sum_i^N I_i \times WBD_i \times R_i \times A_i \quad (4)$$

where i^{th} is the forest-type category, I is the annual timber stock increment (m^3/km^2 per year), BEF is the biomass expansion factor, WBD is the basal density (t/m^3), R is the root/shoot ratio, and A is the forest type area (km^2). The annual timber stock increment was obtained from data reported for the Lombardy region in the Italian Inventory of Forest (Gasparini *et al.*, 2009), and BEF , WBD , and R were derived from Federici *et al.* (2008) following Barbagallo *et al.* (2024).

Landslide hazard reduction

Landslide hazard reduction is a main objective of the UN Sendai Framework for Disaster Risk Reduction 2015-2030, and makes a crucial contribution to the UN Sustainable Development Goals (SDGs). Mountainous areas often have to deal with issues related to landslide hazards.

The landslide hazard reduction is included in the “Buffering and attenuation of mass movement” class (Haines-Young and Potschin-Young, 2018) and is defined as “The reduction in the speed of movement of solid material by virtue of the stabilizing effects of the presence of plants and animals [...] that mitigates or prevents potential damage to human use of the environment or human health and safety” (Haines-Young and Potschin-Young, 2018). Although this class includes a broad range of processes (e.g. creep, solifluction, and the movement of material by surface runoff), in this study we focus specifically on landslides. The spatial extent of hazard-prone areas was derived from regional hazard maps that identify zones with high landslide susceptibility, without discriminating among different types of slope processes. Therefore, while the adopted conceptual framework is general, our economic assessment specifically targets forested areas that contribute to mitigating landslide-related risks, consistent with the available data. In this study, the identification of forested areas exposed to landslide hazard was based on the national landslide hazard dataset provided by ISPRA (Trigila *et al.*, 2021), namely the “Mosaatura della pericolosità da frana dei Piani di Assetto Idrogeologico (PAI)”. We considered only areas

classified as P3 (high hazard) and P4 (very high hazard), as these classes represent the most critical levels of landslide susceptibility and are subject to the most restrictive land-use regulations in Italy (Trigila *et al.*, 2021). Although the dataset does not specify the type of landslide, the selection of P3 and P4 zones ensures that our analysis focuses on areas where protective forest functions are most relevant and policy-relevant for risk mitigation and land planning.

The economic value of landslide hazard reduction is typically quantified using the replacement-cost method (e.g. Nolander and Lundmark, 2024; Notaro and Paletto, 2012). This approach rests on the principle that an ecosystem service can be valued by estimating the cost of replacing it with a technological alternative (Dixon *et al.*, 2013). Although replacement cost does not directly measure people’s willingness to pay, it is reasonable when assessing protective forest functions to assume a latent demand for this service would emerge if forest cover were removed (Notaro and Paletto, 2012). Under this assumption, stakeholders would likely pay up to the cost of the most cost-effective engineering solution that provides equivalent reduction to infrastructure and human activities, as well as indirect safeguarding of soils and watersheds from natural hazards (Häyhä *et al.*, 2015). In line with this, the landslide hazard reduction economic value (V_{LRP} , €) was evaluated as:

$$V_{LRP} = C_R \times A \quad (5)$$

where C_R represents the replacement costs (€/km²) and A is the area prone to landslides (km^2). This latter was derived from data referred to 2020-2021 considering only the forested areas. For this study, we referred to the replacement costs with equivalent natural engineering solutions for forests in areas with high geo-hydrogeological risks (Canuti *et al.*, 2001), reported in Notaro and Paletto, (2004) and re-evaluated by De Marchi and Scolozzi (2012) in January 2012. In this study, we used a replacement cost of 25,427 €/km².

RESULTS

Timber production

The mean annual economic value of timber production is found to range from 230,273 ± 69,634 €/year (LSNP - standing timber) to 1,465,110 ± 271,900 €/year (OBRP - roadside timber) (fig. 5). Therefore, the Orobic Bergamasche Regional Park features a general higher economic value of timber production due to the higher volume of annually cut timber (with a total 2011-2023 value of 222,405 m³ and an annual mean value of 17,108 m³/year) compared to the Lombardy sector of the Stelvio National Park (with a total 2011-2023 value of 56,041 m³ and an annual mean value of 4,311 m³/year). In addition, depending on the type of timber price (i.e. standing or roadside) the

timber production value changes. In fact, the roadside timber price is 63.84% $\pm$ 27.91% higher than the standing one.

Considering the different extent of the two parks, the timber production value per km² for the OBRP is 71% more than that of the LSNP considering the entire area of the two parks (i.e. 699.05 km² and 597.72 km², respectively). This difference is reduced to +38% if only the area covered by forests is taken into account (i.e. 321.02 km² and 129.73 km², respectively).

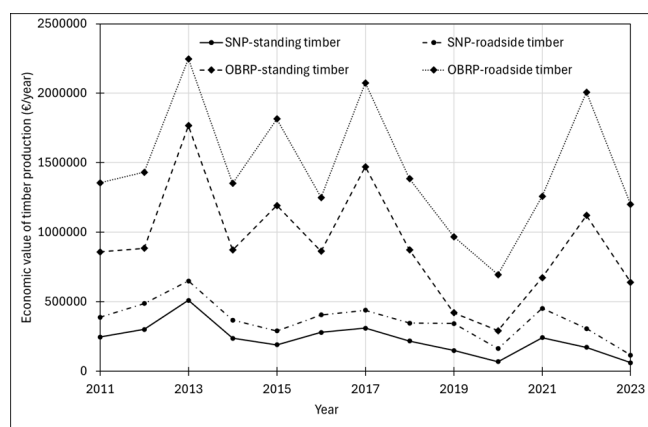


Figure 5 - The economic value of the timber production based on the park (LSNP - Lombardy sector of the Stelvio National Park and OBRP - Orobic Bergamasche Regional Park) and the sale type (standing and roadside).

Carbon sequestration

Annual carbon sequestration differed markedly between the two study areas (LSNP vs. OBRP), both in terms of biomass pools and their economic valuation. In the Stelvio National Park, total above-ground biomass (AGB) amounted to 53,516 t/year, while below-ground biomass (BGB) added another 12,839 t/year. The aggregate economic value of this annual carbon uptake as 152,285 €/year. By contrast, in the Orobic Bergamasche Regional Park, AGB reached 123,389 t/year and BGB contributed 24,034 t/year, corresponding to an economic value of 338,335 €/year (more than twice that of LSNP).

Among individual forest categories (table 1), mountain pines and larches were the leading contributors in LSNP, with AGB of 19,591 t/year and 18,547 t/year, respectively, and a combined Vcs of 109,813 €/year. In OBRP, European beech and Norway spruce (considering only Spruce forests) dominated carbon uptake, with AGB of 34,974 t/year and 34,859 t/year, respectively, and a combined economic value of € 190,056 €/year. Lesser contributions were provided by broadleaf coppices (e.g., chestnut and other broadleaves), while certain shrub- and pine-dominated formations (e.g., Mugo pines, Special formations) sequestered comparatively modest amounts of carbon on an annual basis.

Table 1 - Values of above- and below-ground biomass (AGB and BGB, respectively), and economic values specific to each forest type in the Lombardy sector of the Stelvio National Park (SNP) and Orobic Bergamasche Regional Park (OBRP). The forest categories refer to Federici *et al.* (2008).

Forest categories	Forest types	LSNP			OBRP		
		AGB (t/year)	BGB (t/year)	Vcs (€/year)	AGB (t/year)	BGB (t/year)	Vcs (€/year)
European beech	Beech forests	0	0	0	34,974	5,143	92,070
Larches	Larch forests	18,547	4,409	52,683	13,340	3,171	37,893
Mountain pines	Mugo pine	19,591	5,303	57,131	4,995	1,352	14,565
Norway spruce	Spruce/beech forest	0	0	0	80,74	1,815	22,695
Norway spruce	Spruce forests	9,821	2,208	27,606	34,859	7,837	97,986
Other broadleaves-stands	Maple-ash forests and maple-linden forests	11	2	29	2,233	365	5,962
Other broadleaves-stands	Birch forests and horn-beam forests	279	46	746	233	38	623
Other broadleaves-stands	Unclassified wooded areas	2	0	5	29	5	76
Other broadleaves-stands	Hop-hornbeam forests	0	0	0	9,622	1,571	25,686
Other broadleaves-stands	Anthropogenic (man-made) formations	0	0	0	195	32	521
Other conifers	Scots pine forests	1,460	309	4,059	200	42	555
Riparian vegetation	Alder forests (alder groves)	3,795	558	9,989	6,555	964	17,256
Shrublands	Special (particular) formations	11	5	36	51	21	166
Silver fir	Fir forests	0	0	0	7,992	1670	22,175
Sweet chestnut (coppices)	Chestnut forests	0	0	0	38	8	104
Total		53,516	12,839	152,285	123,389	24,034	338,335

These results underscore the central role of mixed and conifer-dominated stands in regional carbon dynamics and highlight how park-level differences in species composition translate into both biomass accumulation and ecosystem service valuation.

Considering the different size of the two park areas, the economic value per unit area is slightly higher in LSNP (1,174 €/year/km²) compared to OBRP (1,056 €/year/km²), thus an opposite result to those obtained when considering the parks as a whole. This is due to the different forest composition. In fact, considering the different forest types (Table 1), in the Lombardy sector of the Stelvio National Park the economic value ranges from 5 €/year for unclassified wooded area to 57,130 €/year for Larch-Swiss stone pine forests and Swiss stone pine forests. In the Orobic Bergamasche Regional Park, the economic value ranges from 76 €/year for unclassified wooded areas to 97,986 €/year for spruce forest. Therefore, the unclassified wooded area is the forest type with the lowest Vcs value for both parks.

Landslide hazard reduction

The Lombardy sector of the Stelvio National Park is characterized by a slightly wider forest area with high landslide hazard (15.29 km², equal to 12% of forest area, fig. 6), compared to the Orobic Bergamasche Regional Park (14.59 km², equal to 5% of forest area, fig. 7). Considering the whole park areas (i.e. not only forest areas), the high landslide hazard affects 8% of total LSNP area (50.78 km²) and 4% of total OBRP area (28.29 km²).

As the extent of the high landslide hazard areas is similar in both parks, LSNP forests feature a slightly higher economic value of landslide hazard reduction (€ 388,779) compared to OBRP (€ 370,980).

DISCUSSION

Market-driven variability in ES economic valuation

Both for timber production and carbon sequestration, the methods applied depend on the chosen price, thus affecting the final estimated economic value. This is clearly visible for example in the highly variable trend over time of the economic value of timber production shown in figure 5. The collapse in its value after 2018 is due to the effects of the Vaia storm. In fact, at the end of October 2018, the tropical storm Vaia brought heavy rainfall (more than 350-400 mm) and winds of up to 200 km/h to Northern Italy (Chirici *et al.*, 2019), killing 37 people and unleashing damage estimated at almost 5 billion euros. Vaia also affected parts of France, Croatia, Austria, and Switzerland, but Italy sustained the worst forestry destruction in its recent history, with more than 14 million trees felled (Laurin

et al., 2021). Lombardy was one of the regions of Northern Italy mostly affected by Vaia; more than 220 km² of forest were completely destroyed, and over 70% of the damage involved spruce forests (Giupponi *et al.*, 2023). A combination of economic and operational factors (including an oversupply of damaged timber, logistical issues, deteriorating timber quality, and pressure on local markets) created an unfavorable market situation, leading to a significant drop in timber prices in Italy in 2019 (Barbagallo *et al.*, 2024) (fig. 4).

Regarding carbon sequestration, to derive its economic value the social cost of carbon (or its proxies such as the carbon price) is typically multiplied by the expected level of carbon sequestration in forests (Nolander and Lundmark, 2024). Consequently, this evaluation is strongly influenced by the carbon price applied, which can vary dramatically across studies, market contexts and policy frameworks (Richards and Stokes, 2004). The wide range of methodologies used to estimate the costs of carbon sequestration in forests include engineering approaches, market proxies and optimization models, each of which is influenced by factors such as forest type, geographical region, project duration, opportunity costs and policy context. As a result, the estimated costs per ton of CO₂ sequestered vary significantly (also by an order of magnitude) between studies. Richards and Stokes (2004) highlight that these differences are not merely technical, but stem from fundamentally different assumptions about baseline land use, discount rates, leakage and permanence. This price uncertainty leads to considerable variability in the estimated value of ecosystem services, which complicates both comparisons between regions and the formulation of conservation priorities. This variability is due to the diversity of pricing approaches found in the literature and policy frameworks (Richards and Stokes, 2004). The prices can range from a few euros per ton of CO₂ to several hundred euros per ton of CO₂, depending on the methodology chosen. For example, conservation projects in European forest areas, including those related to the protection and management of mountain forests, apply values ranging from 5 to 20 €/tCO₂, depending on the environmental certifications adopted (Ekholm, 2020; Russo *et al.*, 2023). Moreover, The choice of carbon price reflects underlying assumptions about: i) market-based pricing (e.g. EU ETS), which is influenced by supply and demand dynamics, regulatory caps and trading behaviour; ii) social cost of carbon (SCC), which estimates the economic damage per ton of CO₂ emitted and is often used in policy-oriented assessments and integrated assessment models; iii) voluntary carbon markets, where prices may reflect co-benefits or project-related factors.

Finally, even the value of landslide hazard reduction can vary, but in this case depending on the chosen cost (and not price). In this study, we applied the replacement

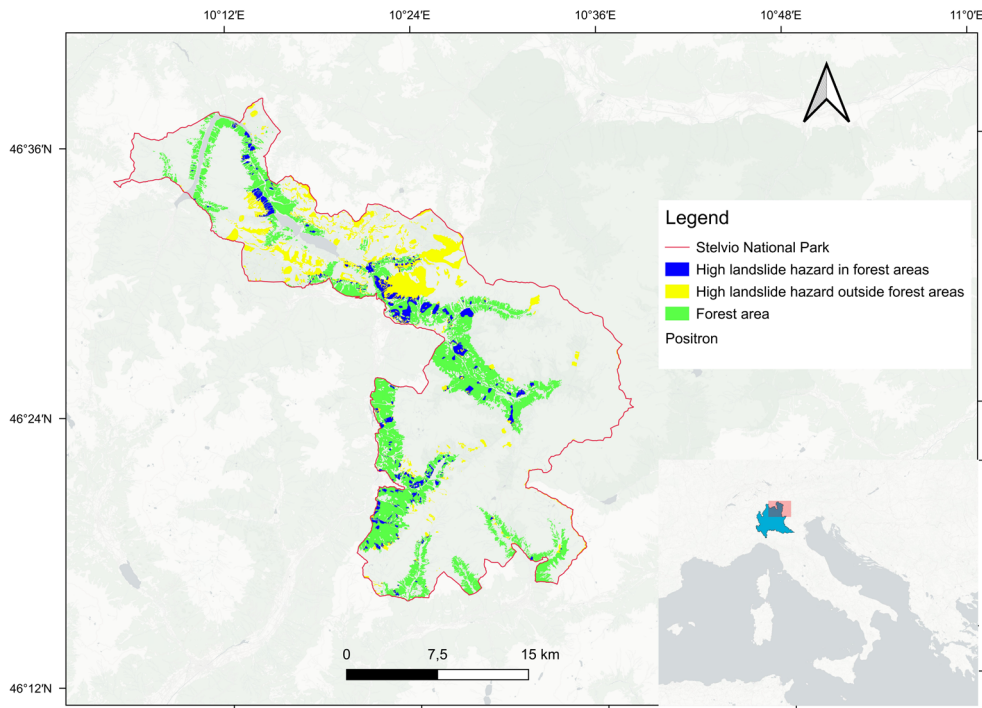


Figure 6 - Forest areas with high landslide hazard in the Lombardy sector of the Stelvio National Park.

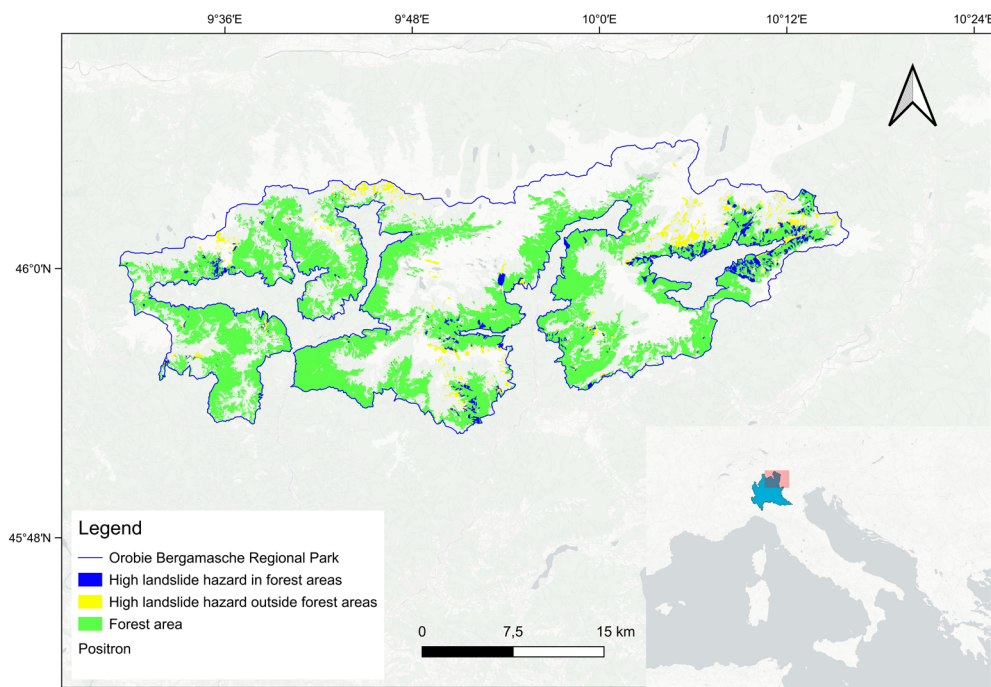


Figure 7 - Forest areas with high landslide hazard in the Orobie Bergamasche Regional Park.

cost method, that requires knowing the replacement cost that citizens will pay or have paid, and therefore it is assumed that the service must be worth at least as much as citizens would have to pay to replace it. As reported by Häyhä *et al.* (2015), when applying the replacement cost method, the following conditions must be met: i) the engineered system provides the same functions as the origi-

nal ecosystem (i.e., it is a close substitute for the replaced service), ii) the engineered system is the least expensive alternative for the service, and iii) there is public demand for this alternative, meaning that people would be willing to pay the cost rather than lose the service. Landslides can cause enormous human and economic losses in mountainous regions (Dai *et al.*, 2002). To effectively

prevent landslide hazards, specific methodologies need to be applied to better understand landslide hazards and to make rational decisions on the allocation of funds for landslide risk management. For this reason, the pricing of ecosystem services related to landslide hazard reduction can be a useful tool.

Comparative analysis of the seven main forest categories

For better discussing the role played by each forest category and then to better understand the differences in ESs economic value between the two parks, we conducted a comparative analysis of the seven main forest categories (fig. 8). We then calculated the economic value of carbon sequestration by considering a unit area occupied entirely by a single forest category. Instead, for timber production we took into account only the timber price for each category, because we did not have available information about the specific forest types involved in the cutting. We considered the prices reported by the LegnoNordOvest portal (developed and managed by IPLA S.p.A., funded by the Piemonte and Liguria Regions, and owned by the Piemonte Region). The price data are updated to March 2024 and refer to standing timber.

Regarding timber production, the highest price is associated to larches (53.91 €/m³), while the lowest one to Norway spruce (12.11 €/m³). Considering the economic value per surface unit of carbon sequestration for each forest category, it emerged that mountain pines feature the highest economic value (1,367 €/km²/year), followed by silver fir (1,356 €/km²/year). On the other hand, the European beech is the category with the lowest Vcs value (1,005 €/km²/year). Summarizing, larches maximize timber production given their high price but rank fourth in terms of carbon sequestration (after mountain pines, silver fir, and other conifers). Conversely, mountain pines maximize carbon sequestration but have the second-lowest timber price.

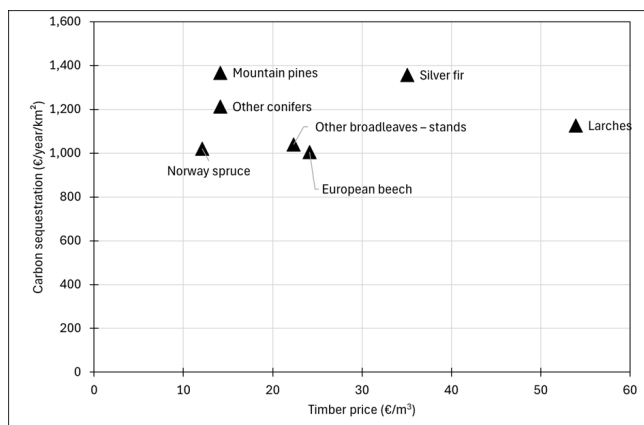


Figure 8 - Timber price (€/m³) and carbon sequestration economic value (€/year/km²) for all the seven main forest categories.

Comparison of landslide types in Stelvio and Orobie Parks

To further interpret the spatial distribution of hazard-prone forest areas, we integrated our analysis on landslide hazard with data from two complementary national datasets. The Inventory of High-Altitude Landslides in the Italian Alps (CNR and IRPI, 2023) documents 1,120 slope instability processes that occurred above 1500 m a.s.l. between 2000 and 2023. It is important to note that the inventory does not refer exclusively to landslides as defined by the Varnes classification system (Hungr *et al.*, 2014), but rather includes a broader range of slope instability processes, such as debris flows, rockfalls, ice avalanches, and complex mass movements that affect high-altitude alpine terrain. The most frequent processes were debris/mud flows (443 events, 39.6%) and rockfalls (332 events, 29.6%). At the regional scale, the most affected areas are Valle d'Aosta (415 events, 37.1%), followed by Trentino-Alto Adige (296, 26.4%), Lombardy (164, 14.6%), and Piedmont (162, 14.5%).

Within Lombardy, our two study areas account for a total of 60 documented events, with 48 in the Stelvio National Park and 11 in the Orobie Bergamasche Regional Park. In LSNP, dominant processes include rockfalls (13 events), debris flows (12), and landslides (9). In OBRP, the most frequent processes are blockfalls (5) and landslides (2).

Additionally, by cross-checking the hazard zones derived from the PAI mosaic (P3-P4 classes) with the Lombardy Landslide Inventory (IFFI; Regione Lombardia, 2020), we were able to better characterize the types of instability processes affecting the areas classified as high hazard. This control analysis revealed that, within the two parks, these zones are exclusively affected by rapid debris flows and rotational slides, which are the only types recorded in the IFFI dataset for these locations.

Beyond the statistics, landslides have profound and lasting impacts on alpine landscapes. Catastrophic events such as those in Val Pola in 1987 (Govi *et al.*, 2002) are emblematic of the territorial fragility of mountain regions, where mass movements can permanently alter the morphology, destroy entire settlements, and impose devastating social and economic costs. These considerations highlight the need to strengthen landslide forecasting, prevention, and early warning systems in the context of a changing climate.

CONCLUSION

This study provides a comparative evaluation of key ecosystem services in two neighbouring protected areas, the Lombardy sector of the Stelvio National Park (LSNP) and Orobie Regional Park (OBRP). OBRP exhibited substantially higher provisioning and regulating services, with annual carbon sequestration valued at 338,335 €/year, more than double that of LSNP (152,285 €/year). Similarly, the average annual timber production value considering market

prices for standing woods in OBRP ($918,044 \pm 242,242$ €/year) and roadside-harvest timber ($1,465,110 \pm 271,900$ €/year) exceeded those in LSNP $230,273 \pm 69,634$ €/year and $366,450 \pm 82,497$ €/year, respectively). In contrast, LSNP demonstrated a marginally greater landslide replacement-cost (€388,779 vs. €370,980), reflecting its steeper terrain and increased geomorphological hazard exposure.

These differences highlight the influence of geological context, species composition and management practices on ecosystem services delivery. While forest carbon dynamics and timber provisioning remain critical, our findings underscore the need to broaden the analytical scope. Integrating additional services, such as cultural one (recreational and aesthetic), hydrological regulation and biodiversity functions, will yield a more comprehensive ecosystem valuation.

In particular, cryosphere-related services warrant targeted investigation in these alpine regions. Future research should incorporate high-resolution remote sensing and ground observations to quantify water storage, glacier melt contributions and dynamics. Economic valuation methods, including choice experiments and cost-benefit analyses, can then appraise services such as downstream water provisioning and flood regulation. Expanding the study to encompass Alpine grasslands, peatlands and periglacial environments will further elucidate trade-offs and synergies among ecosystem services.

AUTHORS CONTRIBUTION

All authors contributed equally to the conception and design of the study, data collection and analysis, and the writing and revision of the manuscript. All authors read and approved the final version of the paper.

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DATA AVAILABILITY

Data are available on request to corresponding author.

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