

Article

Identifying Landscape Characteristics That Maximize Ecosystem Services Provision

Yanina Benedetti ^{1,*} , Federico Morelli ^{1,2}, Marek Svitok ^{3,4,5} , Riccardo Santolini ⁶, Petra Kadlecová ⁷ , Alice Cavalli ⁸ , Andrea Strollo ⁸  and Michele Munafò ⁸ 

- ¹ Department of Ecology, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-165 00 Prague, Czech Republic; fmorellius@gmail.com
 - ² Institute of Biological Sciences, University of Zielona Góra, Prof. Z. Szafrana St. 1, PL-65-516 Zielona Góra, Poland
 - ³ Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, T. G. Masaryka 24, SK-960 01 Zvolen, Slovakia; svitok@tuzvo.sk
 - ⁴ Department of Forest Ecology, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-165 00 Prague, Czech Republic
 - ⁵ Slovak Academy of Sciences, Plant Science and Biodiversity Center, Institute of Botany, Dúbravská Cesta 9, SK-845 23 Bratislava, Slovakia
 - ⁶ Department of Humanities, Università degli Studi di Urbino Carlo Bo, 61029 Urbino, Italy; riccardo.santolini@uniurb.it
 - ⁷ Department of Landscape Architecture, Faculty of Agrobiological Sciences, Czech University of Life Sciences Prague, Kamýcká 129, CZ-165 00 Prague, Czech Republic; kadlecovap@fzp.czu.cz
 - ⁸ Italian National Institute for Environmental Protection and Research (ISPRA), Department of Geological Survey of Italy, Via V. Brancati 48, 00144 Rome, Italy; alice.cavalli26@gmail.com (A.C.); andrea.strollo@isprambiente.it (A.S.); michele.munafò@isprambiente.it (M.M.)
- * Correspondence: ybenedetti73@gmail.com

Abstract: Given global changes and the loss of ecosystem services, it is crucial to assess the effects of landscape characteristics on ecosystem service distribution for sustainable territory management. Italy's diverse landscapes present an opportunity to study this effect. This study identified optimal elevation and landscape heterogeneity ranges that optimize four ecosystem service provisions across Italy. We mapped ecosystem services across Italy using generalized additive models (GAM) to assess their spatial relationships with landscape characteristics, such as elevation and heterogeneity, and specifically, we identified their optimal values concerning elevation and landscape heterogeneity. In Italy, agricultural production is concentrated at low altitudes, like the Po Valley, while the pre-Alps and Apennines regions at intermediate altitudes provide ecosystem services like timber production and carbon storage. However, elevation gradient and landscape heterogeneity significantly influence trade-offs between agricultural production and these services. The optimal altitude for timber production, carbon storage, and habitat quality is around 1500 m above sea level, while agricultural production peaks at the lowest and highest elevations. Our study shows landscape features' significant role in supporting specific ecosystem services. This information is crucial for guiding land use planning and management decisions, especially under global land use and climate change.

Keywords: agricultural production; altitude; carbon storage; habitat quality; landscape heterogeneity; land use planning; Shannon-index; sustainability; timber production



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1. Introduction

Climate change and land cover alterations negatively impact land availability, resulting in economic losses and harm to human well-being [1,2]. Soil is a limited, non-renewable resource essential for human well-being and ecosystem functions [3]. It is a fundamental resource that provides essential functions and ecosystem services (ES) [4]. However, its degradation across several transformation processes leads to its continual loss, impacting

water and air quality, biodiversity, and nutrition for humans and animals [5]. Hence, it is crucial to use soil appropriately to protect the soil resource from various threats such as erosion, contamination, compaction, loss of biodiversity, salinization, landslides, floods, and desertification [1,3]. Adopting more effective management strategies to preserve and restore key ecosystems to enhance environmental resilience to changes is needed [3]. Hence, comprehending the spatial arrangement of environmental resources is fundamental to developing successful management strategies for conserving ecosystems [6].

A strong interest in ecosystem assessments has emerged recently [7]. ES are the ecological features, functions, or processes influencing direct or indirect sustainable human well-being [8]. Ecosystems and ES are strongly correlated [9,10]. Thus, ecosystems provide goods and services to humans and support biodiversity [11], which has key roles in different ecosystem service hierarchies [12]. Accordingly, several studies have emphasized the capacity of biodiversity to provide different products and ES to people [11]. Furthermore, these studies have demonstrated the connection between biodiversity, ecosystem functions, and ES [13]. The quantification of the ES provided is one of the main challenges of protecting environmental resources to balance ecosystems and human well-being [14,15]. Therefore, ecosystem assessment is an effective approach for ensuring the knowledge required for decision-makers from the global to the local level. Often, local administrators are involved in major decisions that influence soil consumption and face the erosion of ES with insufficient technical knowledge and inadequate tools [16,17]. Several studies have focused on ES to understand how living organisms interact and provide these services [4,18]. They concluded that a deeper knowledge of the spatial distribution of multiple ES at a large spatial scale is essential [16,19,20] for making better decisions and policies to maximize their provision efficiently [2,21,22].

Increasing sustainable management of natural resources through providing multiple ES requires assessing the influence of landscape drivers on their spatial distribution [23]. Several studies demonstrated the effect of landscape features on ecosystem service provisions [23–25]. Elevation is an extremely influential environmental variable for ES provisioning. Studies on forest dynamics [26], forest density and species distribution [27], and variation in growth dynamics [28] show the great variability of the effects of elevation on natural resources. Coffee delivers multiple ES from common crops when elevation is considered for agroforestry management [29,30]. Landscape heterogeneity is essential for biodiversity in agricultural systems [31–33], supporting a wide range of ES provisions [9,34–36]. However, landscape structure is simplified in cultural landscapes [37,38]. In the Mediterranean, the abandonment of typical human activities leads to the conversion of a complex landscape matrix into a more homogeneous system, adversely affecting the total diversity of the area [39,40]. Most studies on the effect of landscape heterogeneity on ES were developed on single landscape types, such as agricultural and forest ones. However, considering all environmental types, a more comprehensive assessment would provide a deeper understanding of the complex interactions between landscape heterogeneity and ES provision. From this perspective, the Italian peninsula is largely hilly. Across an elevation gradient, its mountainous land covers 40% of the territory, and plains cover 23.2% [41–43]. Thus, with its wide range of landscapes and heterogeneous topography, the Italian territory could represent an ideal model for studying how various ES respond to global challenges like different climate change scenarios.

Protecting the environment, recognizing the value of natural resources, and preserving our heritage are crucial, especially when facing unique challenges due to climate change [1]. Limiting land consumption and promoting natural capital, quality construction, urban regeneration, and the reuse of contaminated or abandoned areas are necessary to ensure the sustainable restoration of territories [1]. Considering that biodiversity and ES supply are focal points in conservation planning [44], strategies for land use management are usually aimed at conserving biodiversity and other natural values [45]. Therefore, identifying the link between landscape drivers and ES could help identify spatial supply and demand areas for ES and disclose trade-offs and synergies to be considered for efficiently prioritizing ES

conservation and restoration areas by land managers [46–48]. Our study aims to determine the optimal landscape heterogeneity and elevation ranges that maximize the provision of four different ES across the Italian territory at a fine spatial resolution. To achieve this, we had three specific objectives: (1) to analyze the spatial distribution of each ecosystem service, (2) to investigate the relationships among all ES, and (3) to identify the landscape variables range in which each ecosystem service is maximized to determine the priority areas for cost-effective land use planning and biodiversity conservation.

2. Materials and Methods

In this study, we used proxies for four different ES: agricultural production, timber production, carbon storage and sequestration (hereafter carbon storage), and habitat quality (Table 1), according to Benedetti et al. [9]. All ES proxies were assessed by the Italian Institute for Environmental Protection and Research, ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale), by mapping them with the software of InVEST models [49] provided by the Natural Capital Project (<https://naturalcapitalproject.stanford.edu/invest/>, accessed on 10 January 2018). InVEST models evaluate the biophysical and economic attributes of 17 types of ES, which can be grouped into the four categories recommended in the Millennium Ecosystem Assessment [7]. The InVEST models assess the capacity of each land use type to provide different types of ES, using the Corine Land Cover map [50] with high-resolution layers. This study used existing and well-established data at national and international levels, including a validated land use and land cover map, which can be found at De Fiorvante et al. [51]. Additionally, to assess carbon storage, we utilized the organic carbon map from the Global Soil Organic Carbon Map (GSOCmap) [52] and the National Inventory of Forests and Forest Carbon Stocks (<https://www.inventarioforestale.org/it/>, accessed on 10 January 2018). For crop and timber production, we relied on the average agricultural values, which are official data from the Italian Revenue Agency (<https://www.agenziaentrare.gov.it/portale/web/guest/schede/fabbricatiterreni/omi/banche-dati/valori-agricoli-medi>, accessed on 10 January 2018). A more detailed description of ES proxy estimation is provided by Munafò [1,53]. The spatial resolution for ES, such as agricultural production, timber production, carbon storage, and habitat quality values, is 20 m [1,9]. To identify the four ecosystem service types across the entire Italian territory, we applied an up-scaling procedure [54] by utilizing a national grid of 1×1 km grid cell, as shown in Figure 1. Following, the mean value of each ecosystem service was calculated for every spatial unit by using the simple areal weighting disaggregation method as proposed by Wang [55] by considering the relative contribution of source units to the target unit area of a 1×1 km grid cell.

Table 1. List of the four ES explored in this study. All ESs were measured as mean values in each spatial unit (1×1 km grid cell), explaining the main ES proxies.

ES	Type	Units	Notes
Agricultural production	Provisioning	€/ha	The average of agricultural productivity values associated with all cultivated agricultural systems [49].
Timber production	Provisioning	€/ha	The average agricultural productivity values are associated with all forest classes [49].
Carbon sequestration and storage	Regulating	t/ha	The term refers to ecosystems' ability to store greenhouse gases and their contribution to mitigating climate change. Estimating this service generally involves calculating the total amount of organic carbon stored by each type of land use/cover [49,56].
Habitat quality	Supporting	€/ha	It refers to the ecosystem's ability to provide suitable conditions for individual and population survival [49,57].

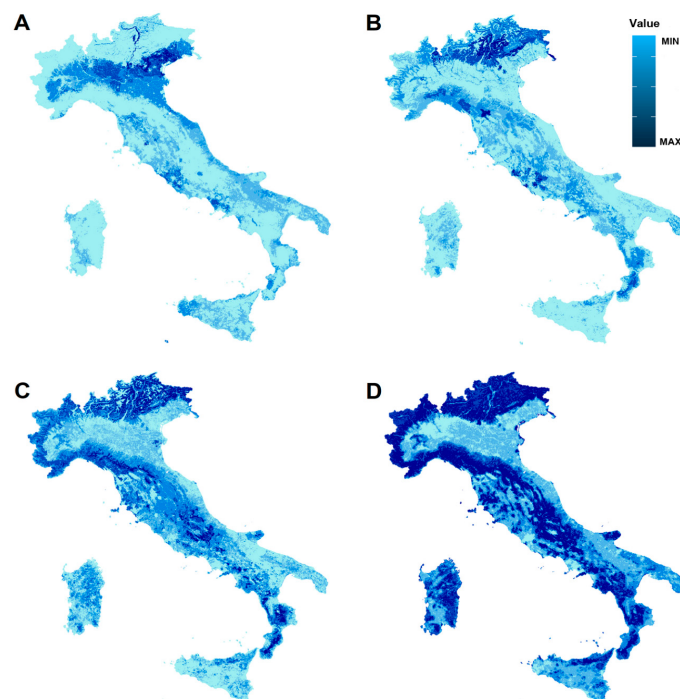


Figure 1. Spatial distribution of ecosystem services assessed in Italy. Each square represents different ecosystem services at the fixed spatial scale of 1×1 km grid cells: (A) agricultural production, (B) timber production, (C) carbon storage, and (D) habitat quality. The values are presented in graduated-scale symbols from lighter blue (lowest values) to darkest blue (highest values).

We employed data from the Shuttle Radar Topography Mission (SRTM) version 4.1 [58] in decimal degrees and datum WGS84 to assess the European elevation gradient. The elevation data of the USGS/NASA SRTM data was transformed into a continuous topography surface through interpolation methods [59]. The mean elevation (m) was assessed in each 1×1 km grid cell using ‘zonal statistics’ from Spatial Analyst tools in ArcGIS 10.1 [60]. The land use types and landscape heterogeneity (Shannon index and weighted edge density) considered in this study were assessed following the procedure described in Benedetti et al. [9].

We chose two metrics from the several landscape metrics available for ecological studies [61,62], trying to follow a cost-effective strategy. The metrics used describe two important landscape characteristics, examining mainly aspects of landscape composition (e.g., evenness or Shannon diversity index) and configuration (weighted edge density). Previous studies have focused on both metrics and shown potential biodiversity surrogacy [63,64]. The Shannon diversity is a good indicator of the land cover diversity. It is potentially associated with the overall biodiversity due to the number of available habitats [65,66]. The weighted edge density is strongly associated with the presence of linear elements, such as hedgerows, tree lines, etc., increasing the overall landscape heterogeneity and the border effect and potentially significantly affecting biodiversity [64,67].

Generalized additive models for location, scale, and shape (GAMLSS) [68] were used to assess distribution patterns of four ES along landscape gradients (LG), such as elevation gradients and landscape heterogeneity. GAMLSS is a flexible semi-parametric statistical framework that extends traditional generalized linear (GLM) and additive (GAM) models beyond the exponential family. GAMLSS allows implicit modeling of all parameters of the distribution of the response variable (i.e., location–mean, scale–variance, and shape–skewness, kurtosis) as (non)linear or smooth functions of the explanatory variables. Regarding heteroscedastic ES data analyzed here, flexible GAMLSS outperformed standard

GAM with constant scale parameters regarding model fit and prediction error. We fitted each ecosystem service with the following Gaussian location-scale model:

$$ES_i \sim N(\mu_i, \sigma_i^2)$$

$$\mu_i = f_1(LG_i) + f_2(Lon_i, Lat_i)$$

$$\log(\sigma_i - b) = f_3(LG_i) + f_4(Lon_i, Lat_i)$$

where μ and σ are location and shape parameters, f_1 – f_4 are penalized smooth functions with a thin plate regression spline basis [69], and b is a lower bound on σ_i set to 0.01 to avoid singularities in the likelihood caused by the standard deviation tending to zero [70]. The location and scale parameters were modeled depending on a given landscape gradient and geographic position (Lat–latitude, Lon–longitude). Isotropic smooths of geographic coordinates (UTMs) were included to account for spatial autocorrelation inherent in the grid GIS data. Following the informal basis dimension tests [71] and check of spatial autocorrelation in the residuals [72], we set the basic dimension for geographic smooths to $k = 500$. Some skewed ESs (agricultural productivity and timber productivity) were log-transformed before analysis to avoid using non-Gaussian models, which would cause high computational costs in modeling these massive data. We fit 18 separate GAMLSS (a single model for each combination of ES and LG) on a training set of 20,000 observations. The models were displayed graphically, with their 95% confidence intervals accounting for the uncertainty in smoothing parameter estimates [73]. The predictive performance of each model was validated on a testing set of 10,000 observations that were left out of the model-building process. Cross-validated median absolute percentage error (MdAPE) was calculated to measure predictive model performance. We extracted the optimum value of LG for each model so that the maximum value of ES is predicted at given (optimal) landscape conditions. Confidence intervals of the optima were estimated by non-parametric bootstrap (100 replicates) using the percentile method [74].

This study examined the trade-offs and synergistic interactions between different ecosystem services in Italy by assessing their spatial congruence. Thus, a partial correlation analysis approach was applied using the R package *ppcor* [75] to determine if paired ecosystem services were positively or negatively associated, with a significance level of α at 0.05. Consequently, a positive correlation between the two ecosystem services indicated a synergistic effect, while a negative correlation suggested a trade-off relationship.

All statistical analyses were performed in R 4.1.3 [76] using the packages *ggplot2* [77], *mgcv* [70], and *ncf* [78].

3. Results

We obtained 308,564 1×1 km grid cells covering Italy, with complete information on four types of ES: elevation, landscape heterogeneity, and land-use composition.

3.1. Spatial Distribution of ES in Italy

The Italian distribution of agricultural production was mainly located in the Po Valley. Meanwhile, lower levels were found in the pre-Alps area and across the Apennines (Figure 1A). Timber production was concentrated mainly in the pre-Alps area. It was less representative in the Po Valley, Sicily, and Sardinia (Figure 1B). Carbon storage was located mainly in the Pre-Alps area and across the Apennines, from the Ligurian to Calabrian Apennines. Meanwhile, it was less representative in the Po Valley and Adriatic coast (Figure 1C). Lastly, habitat quality occurred mainly across the Pre-Alps area, the Apennines, from the Ligurian to Calabrian Apennines, and east of Sicily and Sardinia (Figure 1D).

3.2. Spatial Correlation Among ES

All measured ES demonstrated trade-offs or synergic spatial associations (Figure 2). The trade-offs are represented mainly by agricultural production, which shows negative coefficient correlations with timber production, showing a weak but significant correlation

(Pearson correlation $r = -0.018$, Figure 2), and habitat quality, which displays a stronger correlation (Pearson correlation $r = -0.449$, Figure 2). The synergies were found in the rest of ES. Higher and positive correlation coefficients were found between carbon storage and habitat quality (Pearson correlation $r = -0.614$, Figure 2). Following this, high and positive correlation values were found between habitat quality and carbon storage (Pearson correlation $r = 0.511$, Figure 2), and finally, even if weak, significant synergy was found between carbon storage and agricultural production (Pearson correlation $r = 0.093$, Figure 2).

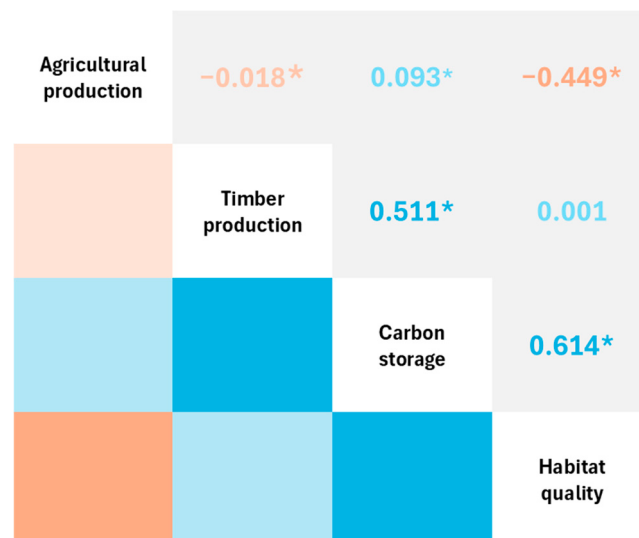


Figure 2. Matrix of the partial correlation analysis based on Pearson correlation coefficient. The variables: Agricultural production ES, Timber production ES, Carbon storage ES, and Habitat quality ES. The positive correlations are indicated in orange squares, and the negative ones in blue squares. The values are presented in the graduated scale from lighter (lowest values) to the darkest color (highest values). Significant correlations are indicated with an asterisk.

3.3. Identifying the Landscape Variables Range in Which Each Ecosystem Service Is Maximized

All assessed ES showed significant relationships with landscape gradients, as revealed by GAMLSS (Figure 3). The predictive performance of the models was generally good for habitat quality and carbon storage (cross-validated error of prediction $\leq 20\%$). In comparison, the prediction of the other ES was rather weak ($>50\%$). Considering optimal landscape conditions that support the highest values of ES, altitudinal optima of timber production, carbon storage, and habitat quality match well at mid-elevations around 1500 m asl (Figure 4). In contrast, agricultural production peaked at the opposite ends of the elevation gradient (-6 vs. 4282 m asl) (Figure 4). When focusing on the Shannon index and Weighted edge density, agricultural and timber production largely overlap in their expected optima. However, the agricultural and timber production confidence intervals were very wide, especially along the edge density (Figure 4). Similarly, optimal conditions for carbon storage and habitat quality coincide with the Shannon index and Weighted edge density gradients (Figure 4).

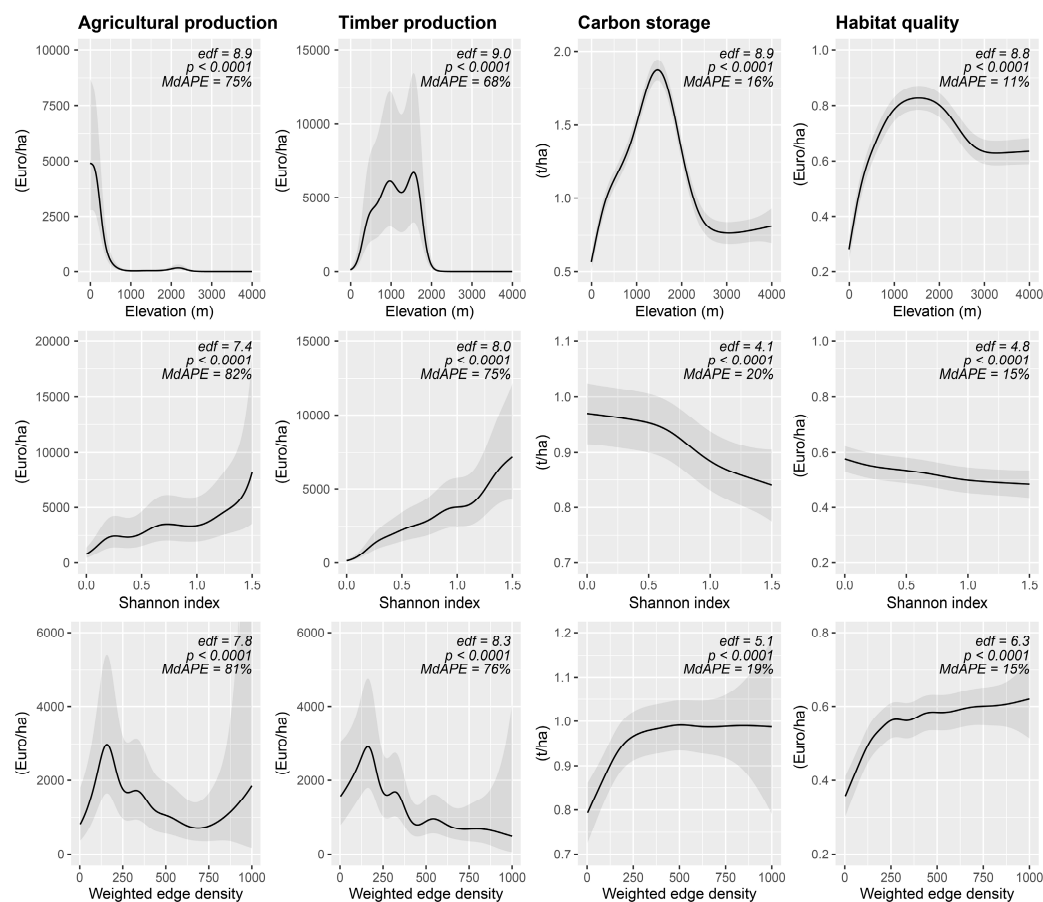


Figure 3. GAMLSS relates four ES to elevation, Shannon index, and Weighted edge density. Model predictions (curves) and 95% confidence intervals (grey bands) are displayed while keeping geographic coordinates at their mean values. Estimated degrees of freedom (edf) for location parameters and related probabilities (p) are given for each model, along with cross-validated prediction errors (MdAPE).

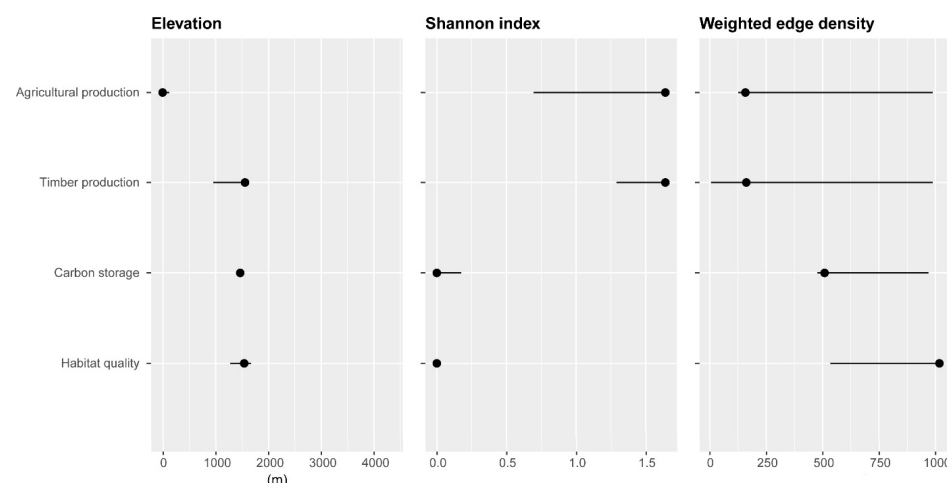


Figure 4. Optima of four different ES along studied landscape gradients derived from GAMLSS. The position of the optima (circles) and their 95% bootstrap confidence intervals (error bars) are displayed.

4. Discussion

Italy's diverse topography offers a rich assortment of landscapes [41–43], making it an excellent candidate for studying how ecosystems respond to global challenges. Therefore,

identifying areas that may be more vulnerable to the failure of ES under global change scenarios (e.g., climate change) is essential for effective conservation and management strategies. Our findings suggest that the spatial distribution of the four evaluated ES in Italy exhibits a remarkable pattern: from one side, the Pre-alps area and the Apennine chain provide higher levels of the studied ES, such as timber production, carbon storage, and habitat quality. On the other side, greater agricultural production levels were mainly found in the correspondence of the Po Valley. Accordingly, these findings highlight the importance of pre-Alps and Apennines territories simultaneously providing high levels of ES. In contrast, the Po Valley territory provides high levels of agricultural production. They emphasize the significance of prioritizing such areas when implementing management and landscape planning strategies to support ES.

It was found that there is a high degree of spatial congruence among various ES, including habitat quality, carbon storage, and timber production, as indicated by positive and significantly higher correlations. The first implication of these results is that conserving a particular ecosystem service (e.g., regulatory one) could also protect the rest of ES, indicating cost-effective conservation planning. On the other hand, the spatial mismatch between agricultural production, timber production, and habitat quality is reflected in the negative associations found. Moreover, agricultural production showed the lowest correlations with habitat quality. These results are similar to those of a study conducted by Crouzat et al. [79], which found that agricultural production was not bundled or overlapped with the other ES examined. Meanwhile, the rest of the ES studied were bundled or partially overlapped [79].

Our results demonstrated significant correlations between elevation gradient and ES focused in this study. The highest values of timber production, carbon storage, and habitat quality services were found around 1500 m asl at mid-elevations. On the other hand, agricultural production was found in the lower and higher elevation values, respectively. These findings are consistent with the outcomes of Schirpke et al. [80], who mapped ES, including forage and timber production, carbon sequestration, and soil stability. They evaluated their distribution based on elevation gradient. This study revealed that higher altitudes have higher timber production values, carbon sequestration, and soil stability. In contrast, agricultural production is negatively related to the increase in altitude. Caddeo et al. [81] assessed similar carbon storage values, mapping the distribution along the Italian peninsula. Due to climatic and pedological heterogeneity, northern Italy had larger values than southern Italy.

Concerning landscape heterogeneity, we found greater values of agricultural production and timber production at greater levels of the Shannon index but lower values of carbon storage and habitat quality. These findings agree with previous studies, such as the one by Duarte et al. [82], which performed a meta-analysis to assess the effect of landscape patterns on several ES. Di Falco and Chavas [83] analyzed the effect of crop biodiversity on agroecosystem productivity in southern Italy using the Shannon index and assessed that diversity is positively related to agricultural production.

On the other hand, we found that agricultural production, timber production, and carbon storage had their maximum provision levels at lower weighted edge density levels. Then, agricultural production and timber production decrease at higher levels. Carbon storage supplies remain constant, and habitat quality increases. These results reflect those observed by Ramirez et al. [84,85], which analyzed the association between watershed landscape fragmentation and ES. It highlighted that the increase in edge density values corresponds to a decrease in the quality of ES (such as soil productivity and maintenance of biodiversity).

4.1. Perspectives Under Different Climate Scenarios

While ES are crucial to mitigate and adapt to climate change [86], they are also vulnerable to its impacts [22]. On the one hand, climate change impacts provisioning services [87] by increasing temperatures, modifying rainfall patterns, and increasing evapotranspiration

rates [43]. Across an altitudinal gradient, we can hypothesize different responses of ES facing extreme climate events. From the plains, the Po Valley's susceptibility to floods and droughts constitutes a pressing concern, given its low elevation and significant agricultural output. According to Spano et al. [43], the Alps and high-altitude areas will experience increased water flow during winter in Italy. Meanwhile, that in the Po River and the Italian plains will experience a decline. Conversely, water scarcity and irrigation demand will increase during the hot season, especially in southern Italy [43]. Thus, changes in weather patterns such as temperature, precipitation, snowfall, and wildfires will directly impact the availability of water resources, affecting agricultural production [88]. Italy's agriculture varies, from intensive farming in northern zones to marginal and shattered farms in the mountain and southern areas [43]. Therefore, proactive measures to mitigate the risks associated with these changes and ensure the sustainability of water resources and agricultural production are essential [89–91].

In pre-Alps and Apennines, ES, such as timber production and carbon storage, reach their highest values. Carbon storage is also a vital regulatory service that helps mitigate the impact of extreme events [88]. In Mori et al. [92], the spatially explicit assessment of supply and demand of regulating ES shows the fundamental role of forests and other vegetated areas whose protection is a priority to assure future flood regulation and associated co-benefits (e.g., regulation of air quality, reduction of erosion, improvement of water quality, and wood fuel). According to Morán-Ordóñez et al. [93], the management policies of Mediterranean forests will have a greater impact on the provision of ES than climate change. Therefore, it is crucial to have decision-support tools and proper environmental management to mitigate the risks associated with climate change, as highlighted by Scholes and Settele [94]. The conservation of forests is essential to protect local ecosystems and communities from unexpected hydrological shifts, as Locatelli [22] emphasized.

4.2. Limitations of the Approach of This Study

Estimating the margin of error for each ES data used in this study is quite challenging. However, it was accomplished for the cartographic base represented by the land use and cover map in the article by De Fioravante et al. [51]. Due to the vastness of the study area, the main challenge in assessing ecosystem services at the national scale is the required generalization of the data. Instead, more accurate data could be found depending on the region, or specific sampling could be conducted on a smaller scale. This would allow for a more nuanced consideration of the varying influence of factors that might affect the estimation of ecosystem services (e.g., climate, soil composition, and specific vegetation types).

5. Conclusions

Our results highlight the role of elevation and landscape heterogeneity on ES, such as agricultural production, timber production, carbon storage, and habitat quality across the Italian territory, evidenced by the different spatial distribution patterns we found at different elevation and landscape heterogeneity ranges. Consequently, establishing priority areas to prevent or reduce habitat fragmentation becomes crucial for supporting sustainable ES and increasing resilience to anthropogenic and global environmental changes (e.g., climate change). Previous studies have investigated the role of landscape drivers in shaping the spatial distribution of ES [23,78,95] but have typically been limited to a small geographic area and a single type of landscape. Our work highlights the importance of altitudes in future conservation planning for ES provision to reduce the vulnerability to global changes (e.g., climate change) and improve ecosystem resilience. Thus, our study aims to contribute new perspectives to land use planning and territorial management at a large spatial scale by taking a wider lens and analyzing multiple landscape types with greater detail.

Finally, considering that many European countries share topographic and climatic similarities with Italy, we suggest that our findings can help develop forecasting models for other countries, particularly those located on the Mediterranean Sea border.

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Data Availability Statement: The datasets used for this study can be accessed as described below: Ecosystem services data: www.isprambiente.gov.it/files/pubblicazioni/rapporti/Rapporto_218_15.pdf, accessed on 1 July 2023; Elevation data: Shuttle Radar Topography Mission (SRTM) version 4.1 (Jarvis et al., 2008 [58]), with datum WGS84 to assess the European elevation gradient (<https://csidotinfo.wordpress.com/data/srtm-90m-digital-elevation-database-v4-1/>, accessed on 1 September 2018); Land use data: www.isprambiente.gov.it/files/pubblicazioni/rapporti/Rapporto_218_15.pdf, accessed on 1 September 2018. No custom codes were used. The codes used for modelling are available from the “ggplot2” (<https://cran.r-project.org/web/packages/ggplot2/index.html>, accessed on 15 October 2022), “mgcv” (<https://cran.r-project.org/web/packages/mgcv/index.html>, accessed on 15 October 2022), and “ncf” (<https://cran.r-project.org/web/packages/ncf/index.html>, accessed on 15 October 2022) R packages.

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