

Research article

Integrating citizen science and spatial machine learning for mapping recreational cultural ecosystem services in rural regions

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ABSTRACT

Cultural Ecosystem Services (CES), particularly recreation, contribute to human well-being, local identity, and sustainable tourism. However, quantifying CES remains challenging due to limited spatial data and the absence of scalable computational frameworks, particularly in rural regions. Here, we developed an integrative and transferable framework for rural areas that combines volunteered geographic information from *Greenmapper*, spatial machine-learning modelling (Random Forest, $R^2 = 0.76$), and economic valuation through benefit transfer. Our objectives were to (1) map the spatial distribution of recreational CES, (2) estimate their monetary value, and (3) provide insights into how perceived recreational landscape values can support environmental management and rural regional planning. This approach captures recreational activity as an indicator of how people perceive and value landscapes, helping identify areas where demand for nature-based recreation is highest. The framework was applied to the Basilicata region (Southern Italy), one of the country's most mountainous and rural regions. Spatial modeling results show that recreational demand is concentrated near populated centers and is strongly influenced by terrain slope, population density, road accessibility, natural features, and protected areas such as *Pollino National Park*. The estimated mean value per-visit is €14.64, highlighting the economic relevance of nature-based recreation in rural landscapes. By linking predictive spatial modeling with economic valuation, this study provides a cost-effective and scalable approach for assessing CES demand in rural regions. The results offer practical insights for landscapes planning, Nature-Based Solutions (NBS), and sustainable tourism strategies, supporting CES into regional environmental management and rural policy.

1. Introduction

Natural landscapes provide numerous ecosystem services (ES) (MEA, 2005), including recreational opportunities that enhance physical health, psychological and emotional well-being (Haines-Young, 2023; Romanazzi et al., 2023; Sobhani et al., 2025). Among these, Cultural Ecosystem Services (CES) strengthen local identity, promote sustainable tourism, sense of place, and improve quality of life, contributing to the resilience of marginal areas. However, the increasing demand for recreational activities also pressures ecosystems (Chen and Wu, 2025).

Rural tourism (RT), which expanded in the 1990s, plays a significant role in rural economies, landscapes, and social change (Randelli et al.,

2011). RT helps maintain rural services, prevents population decline, strengthens local economies, and conserves natural and cultural heritage (European Parliamentary Research Service, 2023). These benefits align closely with CES, which emphasize the cultural and recreational values of landscapes (Capriolo et al., 2020; Cheng et al., 2019; Csurgó and Smith, 2021; Hirons et al., 2016).

Despite growing interest in CES, their quantification remains challenging because recreational values are strongly shaped by how people perceive and experience landscapes. Recreational preferences emerge from subjective interactions between individuals, including perceived naturalness, accessibility, and sense of place (Hansen, 2021). Consequently, CES assessments require approaches capable of integrating

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spatial-environmental characteristics and human landscape perception, as landscapes are not solely physical environments, but also as perceived socio-ecological spaces.

Landscape perception (LP) plays a central role in shaping recreational CES because people do not respond only to the physical properties of landscapes, but also to how landscapes are experienced, interpreted, and socially valued. LP can be understood as the interaction between people and landscape features, where recreational experiences are shaped by perceived naturalness, accessibility, aesthetic quality, and sense of place. Recreational landscapes therefore represent socio-ecological systems in which natural and cultural elements jointly influence how environments are valued or experienced (Zhang, 2025).

Additionally, as CES are typically non-monetary services, their value is difficult to capture using conventional economic approaches (Fagarazzi et al., 2021). Within the Millennium Ecosystem Assessment framework (MEA, 2005), CES exhibits weaker linkages to the core components of human well-being than other ES categories. However, this weaker linkage does not imply that CES are less important; rather, their contributions are often indirect, subjective, and difficult to quantify within conventional economic and policy frameworks. Consequently, their value is frequently underrepresented in environmental decision-making.

Current methodological approaches remain fragmented (Krsnik and Illán-Fernández, 2024). Many assessments rely on either social media-derived indicators or spatial regression models alone, without integrating spatial, experiential and economic dimensions of recreational landscapes. As a result, human perceptions and subjective recreational preferences are often incompletely incorporated into environmental management and CES assessment frameworks. Furthermore, most CES studies have focused primarily on urban environments (Chen and Wu, 2025; Yang et al., 2025), while rural areas remain comparatively underexplored.

Mapping of ES is a key tool for integrating the ES approach into decision-making and spatial planning (Peña et al., 2015). Growing attention is also given to ecosystem accounting approaches, particularly the United Nations System of Environmental Economic Accounting - Ecosystem Accounting (SEEA-EA) (United Nations, 2021), which structures information on ecosystem extent, condition, and services flows. Although this study does not develop formal ecosystem accounts, it follows a similar logic by linking spatial analysis with economic valuation.

This research contributes to addressing several gaps in recreational CES research by combining citizen science, spatial machine learning, and economic valuation for assessing rural recreational CES. By identifying spatial patterns of perceived recreational demand, we highlight the importance of landscapes for environmental management (Pasca et al., 2022). By understanding social and cultural needs, we not only promote sustainable tourism but also indirectly support regulating ES (Pei Xia, 2025). Economic valuation acts as a bridge between researchers and decision-makers.

The study aligns with the European Union policy framework “A long-term vision for the EU’s Rural Areas - Towards stronger, connected, resilient and prosperous rural areas by 2040”, which highlights the underrepresented role of rural areas, despite they account for the majority of the EU’s territory. Furthermore, in the context of the European Green Deal (European Commission, 2019), which positions rural areas as key contributors to achieving climate neutrality by 2050, this research supports ecosystem-based development pathways.

This study aims to (1) map spatial demand of recreational CES in Basilicata, (2) quantify their economic value, and (3) provide insights into how perceived recreational landscapes values can support environmental management and rural regional planning. We propose a scalable, low-cost framework for quantifying recreational CES in regions that lack systematic monitoring by integrating citizen-generated data through spatial machine learning and economic assessment.

The following Research Questions (RQs) were set.

RQ1: How can landscape perception and citizen-generated spatial data improve the quantification of recreational CES demand in rural areas?

RQ2: How can the integration of perception-based spatial prediction and economic valuation of recreational CES support NBS and sustainable regional planning in rural contexts?

2. Materials and methods

2.1. Study area

This study focuses on the Basilicata region (40.5°N 16°E), the most mountainous region (47%) in Southern Italy (Fig. 1) (ISTAT, 2023; Pilogallo et al., 2019). The region covers an area of 9995 km² and has a population of 537,577 inhabitants, making it one of the least populated areas of Italy (ISTAT, 2022, ISTAT, 2024). Basilicata is predominantly rural (68%). With 98 rural municipalities out of 131, including 57 mountainous municipalities. Approximately 56.9% of the population resides in “D Area” Rural Areas with Development Problems, according to the Rural Development Program (Spagnoli, 2022).

Approximately 20% of the territory is designated as protected areas (PAs) (Fig. 1, Table 1), including two national parks, Pollino, the largest protected area in Italy, and Appennino Lucano-Val d’Agri-Lagonegrese, along with two regional parks and several nature reserves. This extensive protected area network provides a valuable context for recreational CES assessment in the region (Ministero dell’Ambiente e della Sicurezza Energetica, 2024). Given the region’s rural character, high density of PAs, and significant ecological and cultural value, understanding CES is crucial for supporting sustainable rural development and planning.

2.2. Data input

Our methodology integrates geospatial data from *Greenmapper* (Sijtsma and Daams, 2013), an online questionnaire focused exclusively on natural areas, using responses across all Italy (Fig. 1). The dataset, obtained in March 2025 upon request, includes geocoordinates that allow mapping recreational locations and identifying landscape features influencing recreation choices (Adamowicz et al., 2011; Cozzi et al., 2022). The respondents were predominantly concentrated in younger age groups, particularly between 21 and 25 years (26.64%), followed by 26-30 years (19.71%) and 31-35 years (18.25%). Older age classes (40-80 years) represent 35.4% of the sample. Potential predictors were identified from the literature (Baró et al., 2016; Krsnik and Illán-Fernández, 2024; Sobhani et al., 2025; Wei et al., 2024; Zhang et al., 2025), and initially ten variables were tested (*population density, distances from the main roads, protected areas, slope, Carta della Natura, picnic areas, camper areas, panoramic points, monumental trees, Natura 2000 sites*).

2.3. Data preprocessing

To transform citizen-generated point data into a continuous surface of CES demand intensity at 1 ha resolution, Kernel Density Estimation (KDE) approach was applied.

Data cleaning was conducted to improve accuracy. Firstly, vector points outside the Basilicata were excluded. Secondly, records were classified using *Carta della Natura* (Papallo and Bianco, 2012). Specifically, points located in anthropogenic and agricultural zones were removed, as the study focused on recreational activities in natural environments. Natural environments considered in this study included, according to ISPRA, 2023: classes 1, 2, 3, 4, 5, 6, and 9). Anthropogenic environments (class 8) were excluded from further analysis.

Thirdly, points labeled as “home” were removed, as the study focused on recreational destinations rather than residential locations. Finally, 548 responses out of approximately 8000 were retained for predictive demand modelling.

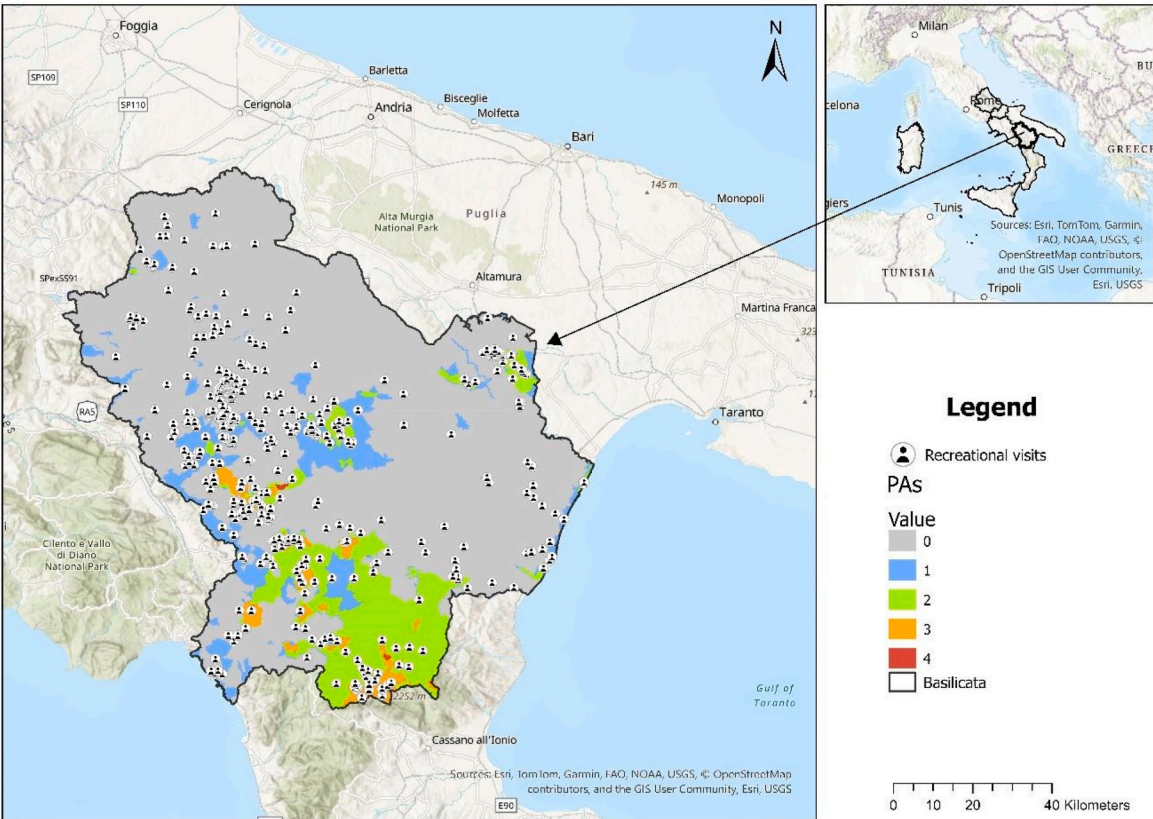


Fig. 1. Protected areas and recreational visits in the Basilicata case study.

Table 1
Variable importance based on the Random Forest model.

Variable	Type/unit	Importance, %	Resolution	Reference
<i>Terrain slope</i>	Continuous/degrees	28	100 m	Calculated from Digital Terrain Model (DTM). DTM derived from (Basilicata, 2025a, RSDI geoportal) (Istituto Nazionale di Statistica (ISTAT), 2024) (Regione Basilicata, 2025b, RSDI geoportal) (Carta della Natura, ISPRA, 2023). Assessed on 15.04.2025 (Ministero dell'Ambiente e della Sicurezza Energetica, 2024; Regione Basilicata; RSDI geoportal)
<i>Population density</i>	Continuous/inh/ha	24		
<i>Distances from the main roads</i>	Continuous/meters	21		
<i>Carta della Natura</i>	Categorical/habitat classes	20		
<i>Protected Areas (Natura 2000 sites, regional parks, natural reserves)</i>	Categorical/Discrete categories (0-4 indicating number/overlap of PAs)	8		

To ensure model robustness 50 Random Forest Regression (RFR) trials were conducted by varying the number of predictors, trees, and train-test proportions. Each trial was evaluated using performance metrics (R^2 , MAE and variable importance) to identify the best-performing model.

Initial model runs included ten variables including with infrastructure-related predictors (*picnic areas*, *camper areas*, *panoramic points*, *monumental trees*). However, these variables did not improve the model performance, confirming that accessibility and landscape characteristics are the primary drivers of predicted recreational demand. These infrastructure-related variables exhibited high spatial clustering and limited spatial coverage. Furthermore, recreational infrastructure is often endogenous to demand (i.e., developed in already attractive and accessible locations). Including such variables may therefore reflect management response rather than underlying ecosystem service potential. For reasons of parsimony, reduced multicollinearity effects, and improved transferability to rural regions lacking detailed infrastructure datasets, these variables were excluded from the final model specification. [Supplementary Fig. S1](#) presents the sensitivity analysis used to identify the optimal number of predictors.

Following the statistical assessment, five predictive parameters were retained ([Table 1](#)). *Natura 2000 sites* were aggregated to protected areas as they partially overlap and represent a similar predictor. The final model achieved an R^2 value of 0.76, including five variables, 400 trees, and a proportion of 0.3, meaning that 30% of the data was allocated for testing and 70% for training, with both sets selected randomly ([Ganesh et al., 2021](#); [Schonlau and Zou, 2020](#)).

2.4. Data requirements and substitution options

Although this study utilized regional datasets from Basilicata, the framework does not depend on high-resolution proprietary data. Each predictor variable can be substituted with globally available alternatives.

- Terrain slope: SRTM or Copernicus DEM (30 m resolution).
- Population density: WorldPop or GPWv4 datasets.
- Road accessibility: OpenStreetMap road network.
- Protected areas: World Database on Protected Areas (WDPA).
- Habitat classification: ESA WorldCover or Copernicus Land Cover.

The reliance on open-access geospatial layers increases the transferability of the methodological framework and allows its application in other rural regions, where institutional datasets may be limited but globally environmental datasets are available.

Our study indicated that the most stable statistical performance was achieved using at least four spatial predictors.

2.5. Methods

The recreation model aims to identify and assess areas with high naturalness potential for ecosystem-based recreation in the Basilicata region, using biophysical and economic methods (Fig. 2). We used Geographic Information Systems (GIS) tools for clipping, spatial analysis, and results visualization and the R (R Core Team, 2025).

2.5.1. Biophysical recreation model

The methodology integrates citizen-generated data on perceived landscapes with predictive variables geospatial data with a *RFR model*, a machine learning technique used to generate predictive maps in GIS. RFR builds multiple decision trees using different subsets of the data and averages their predictions to improve accuracy and reduce overfitting (Sun et al., 2023). Using training data and spatial predictors, the model estimates continuous variables across the study area (Ganesh et al., 2021; Schonlau and Zou, 2020).

The stability and robustness of the model is confirmed by statistical analysis of RFR, indicating a small variation difference between training and validation data. Ecological data are often sparse, noisy, autocorrelated (Boettiger et al., 2013). In our case, Mean Absolute Error (MAE) is 0.674 in training data and 1.325 in validation data (Table 2). In addition, the mean absolute percentage error (MAPE) is 9.63% which states as highly accurate forecasting (<10) according to (Montaño Moreno et al., 2013) Lewis, 1982, p. 40), confirming robustness.

2.5.2. Economic evaluation

As CES are non-market in nature, their quantification remains challenging. Due to the complexity, studies have shown that the economic value of recreational services, a key component of CES, is highly significant (Fagarazzi et al., 2021). Among the available methods, such as *Travel-Cost Method (TCM)*, *Contingent Valuation Method (CVM)*, which uses surveys to directly ask people their *Willingness To Pay (WTP)* for specific environmental benefits; *Resource Rent*, *Hedonic Pricing Method*, *choice experiments*, we adopted the *Benefit Transfer Method (BTM)* (Desvousges et al., 1992) due to data limitations. BTM allows transferring existing values from previous case studies to the target region, following appropriate adjustments.

Our analysis focused exclusively on recreational activities; therefore, studies valuing aesthetic or landscape functions were excluded. Additionally, only natural areas were considered, urban parks were not included in the analysis to maintain consistency with the study's scope.

As the RFR produced relative CES demand values rather than absolute visitor numbers an intermediate calibration step was required before monetary valuation. Since regional statistics on outdoor recreation or nature-based tourism activities were not available for Basilicata, a proxy approach based on tourism presence statistics was adopted by applying the national proportion of rural to total tourism presences to the regional total reported by ISTAT (2023). Tourism categories considered more representative of the natural environment, associated with mountain localities and hilly localities were retained, whereas categories less directly associated with the research scope (marine and thermal tourism) were excluded. The resulting proportion was subsequently applied to the total tourism presences reported for Basilicata by ISTAT, 2023, yielding an estimated value of 87,819 tourism presences potentially associated with rural recreational environments.

To ensure methodological rigor, we conducted a systematic review of recreational valuation studies, identifying 12 suitable values from the literature (Borzykowski et al., 2017; Notaro et al., 2008; Cozzi, 2000;

Darby et al., 2021; Lupp et al., 2016; Ovando et al., 2016; Paletto et al., 2023; Paletto et al., 2024; Sinclair et al., 2022; Willemen et al., 2010). The BTM was applied according to the procedure described by (Richardson et al., 2015), focusing on comparable ecosystem types and geographic contexts, with foreign studies values adjusted for inflation.

Each value was converted to current May 2025 price through a two-step adjustment process: 1) inflation correction using the ISTAT Consumer Price Index (CPI), and 2) income adjustment using the ratio of Italian to source-country per-capita GDP. The adjusted values ranged from €2.60 to €39.56, yielding a mean of €14.64, median of €11.84, and a standard deviation of €11.15, indicating a moderately right-skewed distribution. The mean value was applied as the baseline scenario for monetary aggregation.

3. Results

Our results for recreational activities in the Basilicata region are presented in biophysical (Fig. 3) and economic terms (Fig. 4), and at the municipality level for each method. The analysis highlights the areas with the recreation demand, also indicating their economic importance within the region.

3.1. Biophysical assessment of recreation

The biophysical assessment of recreational activities is illustrated in Fig. 3a, which represents estimated demand based on actual people's responses and variables using a machine learning approach. The demand map is a predictive representation of where recreational CES are likely to be most in demand, based on modelled human preferences. It incorporates citizen-generated data, and five variables from Table 1. Using regression modelling, these factors were used to estimate potential recreational demand across the landscape. Areas with the highest predicted demand indicates areas with the greatest ecological potential to provide recreational CES. In our case, these areas are mainly natural areas, such as lakes and National Parks. Low predicted values occur predominantly in remote mountainous zones. Predicted demand values ranged from 1.03 to 14.79 (mean = 1.86, SD = 0.9), indicating a moderate right-skewed distribution.

Following the methodology proposed by (Chen and Wu, 2025), we applied range normalization to standardize the data, mapping values between 0 and 1 (Fig. 3a), and used the entropy method to objectively determine indicator weights. The normalization equation is as follows:

$$y_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}, \quad (2)$$

Where y_{ij} represents the normalized value of the j -th indicator for the i -th unit area, X_{ij} – raw data, and X_{min} and X_{max} are the minimum and maximum values of the indicator.

Zonal statistics were used to calculate the mean predicted CES value within each municipality, allowing comparison of recreation intensity across administrative units of varying size (Fig. 3b). Municipalities such as: *Policoro*, *Scanzano Jonico*, *Bernalda*, *Senise*, and *Potenza* exhibit above-average CES demand. For visualization, municipal mean values were classified using the Jenks natural breaks method to highlight spatial clustering.

3.2. Monetary assessment of recreation

The spatial assessment of CES related to recreational activities in natural areas revealed a heterogeneous distribution of economic values, ranging from 0 to €21.03 (Fig. 4a). Most of the landscape shows low to moderate values, while only a few hotspots reach the upper end of the spectrum, associated with natural landscapes such as PAs, parks, and lakes. This variability is visually reflected in the CES map, where the dominant blue tones represent widespread low to medium values. In

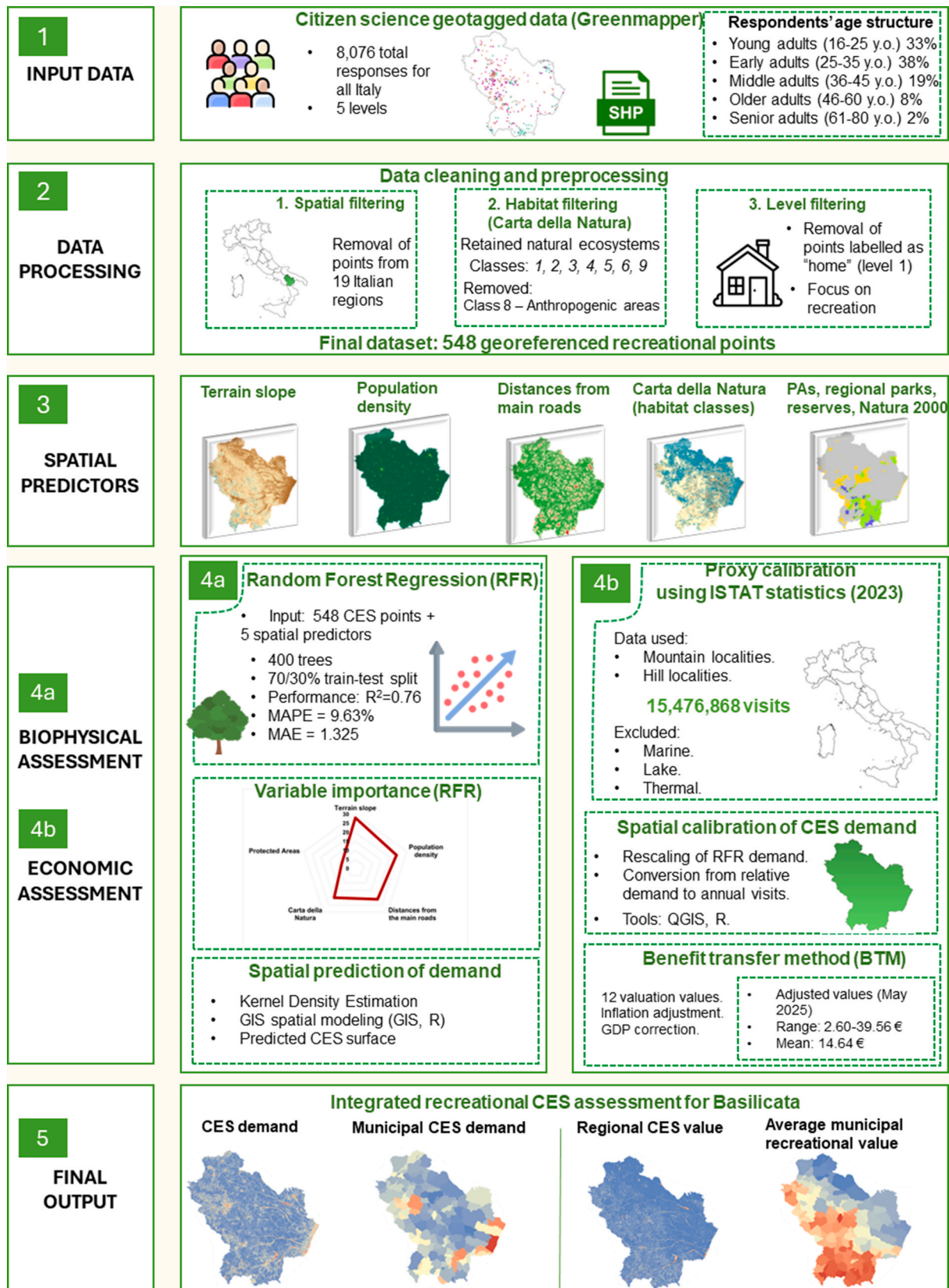


Fig. 2. Methodological framework of the study.

Table 2

Performance evaluation metrics.

	R ²	MAE	RMSE
Train (70%)	0.937	0.674	0.953
Prediction (30%)	0.761	1.325	1.787

contrast, yellow and few limited red areas highlight high-value locations. The observed minimum value of €0 indicates areas with little or no estimated recreational use or cultural service value.

To further evaluate the spatial distribution of CES values, the raster was classified into five quantile-based classes. Results showed that

nearly half of the study area (48.3%) belonged to the lowest-value class, corresponding to areas with null recreational value. Intermediate classes represented 11.7%, 16.4%, and 13.2% of the territory, respectively, while only 10.4% of the region fell within the highest value class (€2.89–€21.03 per visit).

Regional average values (Fig. 4b) are predominantly observed within protected areas and reserves, ranging from €0.24 to €2.58 per visit. The highest regional value occurs in *Castelmezzano*, and throughout the southern part of the region. In contrast, lower municipal averages were predominantly observed in northern and north-eastern parts of Basilicata.

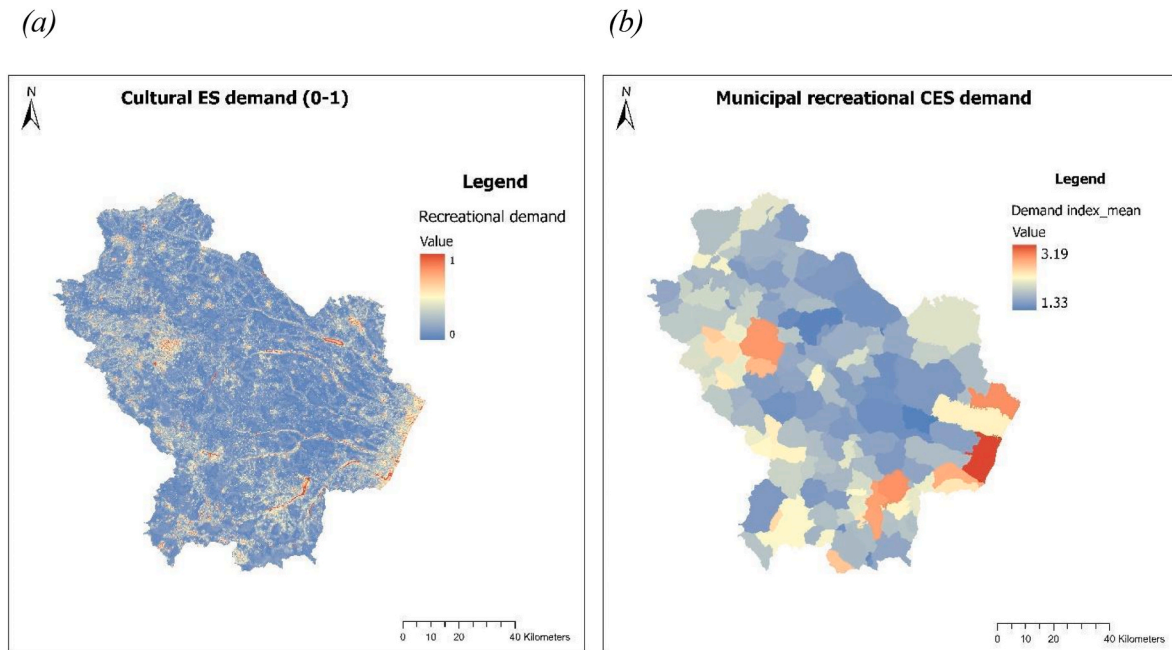


Fig. 3. Spatial modeling of recreational demand in the Basilicata region. (a) Normalized estimated CES demand surface. (b) Municipal-level spatial distribution of recreational CES demand.

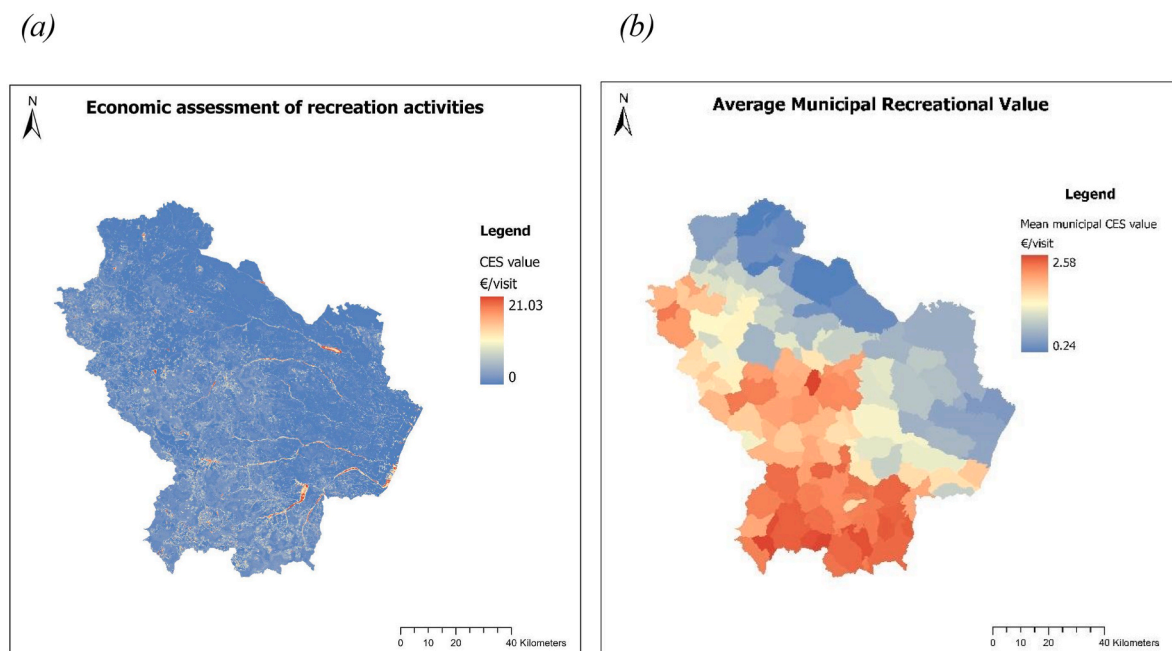


Fig. 4. Economic assessment of demand recreation activities in the Basilicata region. (a) Regional estimated CES value. (b) Average municipal recreational value.

3.3. Practical implications

Although this study does not develop full ecosystem accounts, the framework presented here is conceptually aligned with the SEEA Ecosystem Accounting Approach (United Nations, 2021). By linking ecosystem condition, service flows, and socio-economic benefits, the proposed framework demonstrates how landscape perception can contribute to ecosystem accounting applications supporting regional planning and NBS in rural areas (Fig. 5).

Specifically, the framework highlights the role of landscape perception as a mechanism linking ecological characteristics and human interactions with ecosystems. Rather than representing only a social dimension, LP provides spatially explicit information on how people value ecosystems, allowing cultural dimensions of landscapes to be incorporated into decision-making process.

In particular, Fig. 5 illustrates how natural areas and landscape quality contribute to recreational CES supply, which in turn generates human well-being and economic value for local communities and visitors. These relationships are consistent with the SEEA EA pattern

connecting ecosystem extent and condition with ecosystem service flows and beneficiaries.

4. Discussion

This research contributes to addressing key gaps in recreational CES research by integrating human LP into spatial environmental assessment. The findings suggest that recreational demand is shaped not only by biophysical, and accessibility-related characteristics, but also by how people perceive, and value landscapes. By understanding and linking citizen-generated perceptions with spatial modelling and economic valuation, this study highlights the importance of experiential landscape dimensions into CES assessment and environmental management, with potential implications for sustainable tourism planning, ecosystem conservation, and also indirectly contributes to regulating ecosystem services.

Economic valuation seeks to act as a bridge in communication between researchers and policy-makers by demonstrating the relevance of natural areas through spatial mapping and machine learning. The

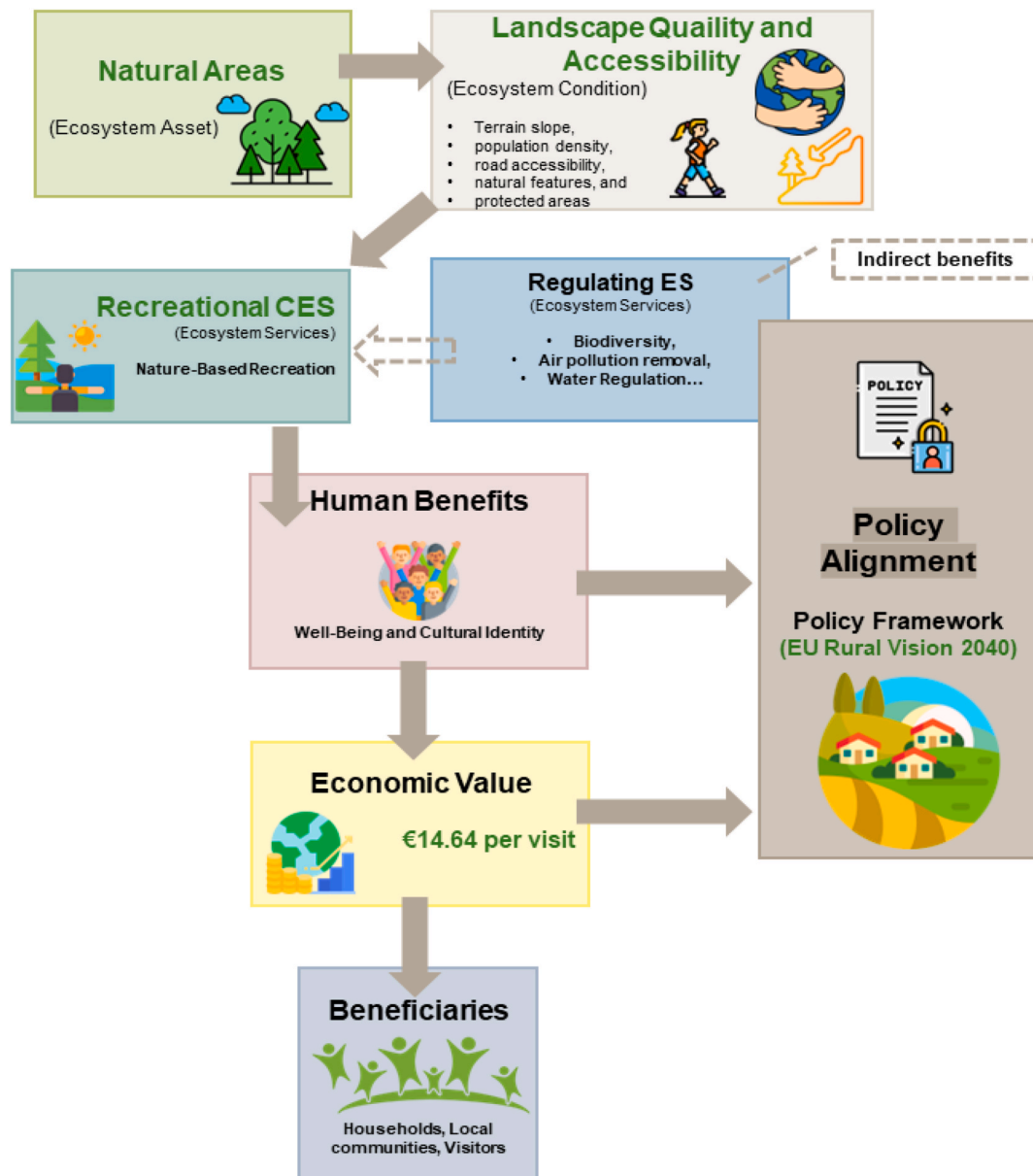


Fig. 5. Recreational ecosystem services within SEEA Ecosystem Accounting and EU Rural Policy.

findings of this study can serve as a direct vector for regional planners in deciding which indicators are the most influential and play a crucial role in increasing the use of NBS. For example, this can include expanding the number of green spaces, preserving protected areas, and improving infrastructure that increases accessibility to long-distance protected areas.

A long-term Vision for the EU's Rural Areas highlights the under-represented role of rural areas. In line with regional development strategies aimed at attracting new businesses, improving infrastructure, promoting sustainable tourism (Pasca et al., 2022), and supporting sustainable rural planning, this study identified spatial patterns of recreational demand, accessibility (Son et al., 2025), and PAs. By supporting sustainable rural planning, young people are indirectly encouraged to remain in rural areas rather than migrate to large cities (European Union, 2021).

4.1. Integrating landscape perception into recreational CES quantification (RQ1)

This study contributes to recreational CES quantification in rural regions by integrating landscape perception, citizen-generated spatial data, spatial machine learning, and economic valuation. Unlike previous CES mapping models based on fixed coefficients, the RFR captures non-linear relationships between accessibility, protection status, and recreation demand, enhancing predictive performance. This improves the capacity to represent complex human-environment interactions and perception-driven recreational behaviors that are typical of heterogeneous rural landscapes. By combining volunteered geographic information reflecting perceived landscape attractiveness with environmental and infrastructural predictors, the model provides a low-cost method to quantify recreational demand in rural areas.

Estimating perceived recreational demand remains challenging (Cordell and Bergstrom, 1989) because it depends on site characteristics and individual preferences (Mukanjari et al., 2021). Additionally, demand patterns grow faster than the supply side (Cordell and Bergstrom, 1989), which further complicates the estimation process. Traditionally, demand curves were derived by estimating the statistical relationship between trips and travel distance to recreational sites (Cordell and Bergstrom, 1989). However, recreational demand has its complexity which includes multiple factors: human perceptions of landscapes (Son et al., 2025), spatial variability (Pellegrini et al., 2025), diverse motivations for visiting nature (Cheng et al., 2019; Kosanic and Petzold, 2020) and broader socio-economic dynamics such as economic growth (Li et al., 2025), which increase recreational demand and make its estimation essential for environmental management. While existing studies using the INVEST tool have provided valuable insights into geotourism and landscape attractiveness, they typically assume fixed human responses to environmental characteristics and may therefore insufficiently capture subjective LP and experiential recreational preferences (Kosanic and Petzold, 2020; Romanazzi et al., 2023). By contrast, the machine learning approach applied here allows flexibility between relationships and landscape features, accessibility, and recreation demand (Schonlau and Zou, 2020; Sun et al., 2023). This approach allows estimating nature-based tourism in a country-specific context to better understand the actual demand. This is particularly relevant in rural areas, due to their disparity and heterogeneity, compared to urban sites (Láng-Ritter et al., 2025); our case study showed that this approach works, where standardized assumptions may not adequately capture actual recreational demand.

Additionally, this study extends beyond identifying CES “hotspots” by linking spatial demand with monetary estimates through benefit transfer. Although monetary valuation captures only one dimension of CES, it provides an additional decision-support tool for comparing recreational benefits with conservation and infrastructure costs. The combined spatial-economic framework is particularly useful in rural regions where systematic visitation statistics are often lacking (Blače et al.,

2024), while also enabling perception-informed environmental management and rural planning.

4.2. Spatial drivers of recreational CES

Results show that predicted recreation is higher in accessible, moderately sloped landscapes than in steep terrain. *Terrain slope* accounted for 28% of variable importance in the RFR (Table 1). Remote areas, despite high perceived aesthetic/ecological value, are less used because physical accessibility strongly influences how landscapes are experienced. Limited recreational demand in remote mountainous zones suggests that physical accessibility remains a key barrier to realizing the region's recreational potential. Recent initiatives in Basilicata, such as the *Volo dell'Angelo* in Castelmezzano and the *Ponte Tibetano* in Castelsaraceno (Corriere della Sera, 2021), illustrate how landscapes can be strategically used for innovative forms of recreational tourism.

Population density (24%) and *distance to major roads* (21%) were also important predictors, showing accessibility strongly shapes recreation patterns. Municipalities with the highest populations show significantly higher average recreation demand compared with the regional mean (3.17 vs. 2.07). These findings are consistent with recent studies emphasizing accessibility and populated centers as key determinant of CES use across different geographic and cultural contexts (Hoofman et al., 2023; Son et al., 2025).

Protected areas show higher predicted recreational demand compared to non-protected areas, reflecting their ecological quality and recreational appeal. Zonal statistics showed a mean value of 2.87 in PAs compared with 1.81 for non-protected areas. Sites such as *Pollino National Park* attract considerable demand due to their ecological and recreational value. Although PAs accounted for 8% in variable importance based on RFR, their spatial representation is marked in red, suggesting they are critical areas for recreational use and cultural services provision, in line with (Benetti and Langemeyer, 2021; Rota et al., 2025; Sinclair et al., 2022).

Pasca et al. (2022) conducted a survey in the Lazio region (Rome, Italy), including 40 respondents in natural PAs, to estimate accessibility. Their results showed that not all parks have sufficient and easy to find information, and 70% of respondents lacked technical route details for disabled people. The findings indicate untapped potential, suggesting the need for sustainable access routes (Rahman et al., 2025), and cultural trails that connect rural and protected landscapes. Different age groups have specific accessibility needs. For instance (Koppen et al., 2014), highlighted that accessibility needs differ between children, adults, and elderly populations.

These spatial patterns provide insights for regional planning and NBS (Corgo et al., 2024). The concentration of high predicted values near accessible natural areas – lakes, protected reserves and peri-urban landscapes, highlighting the role of infrastructure and topography in shaping recreation opportunities. Integrating these insights into planning processes can help target investments in sustainable access, visitor management, and landscape conservation where social demand and ecological value intersect.

While recreational infrastructure represents tangible facilities supporting visitor use, our findings suggest that accessibility and landscape characteristics exert stronger explanatory power at regional scale. Infrastructure may function as a reinforcing factor rather than a primary driver of spatial demand patterns. This distinction is particularly relevant for rural planning, where improving accessibility may have greater systemic effects than isolated infrastructure additions.

Combining spatial and economic analysis is crucial for decision-making in regional planning. Areas with higher natural complexity and beauty tend to be associated with greater economic values. Pei Xia, 2025 showed that lake-related services are multi-dimensional and are best considered as social-ecological systems; their intersection with regulating and social benefits for society. For example, areas with a high number of protected areas and scenic landscapes not only attract more

visitors but also contribute significantly to local economies through sustainable tourism and recreational services.

While monetary valuation captures only part of CES, its integration with spatial modeling provides an additional layer of information. Further analysis indicates that higher economic values are clustered in regions with unique ecological and aesthetic characteristics. Proximity to water bodies and landscape diversity correlates with increased recreational use and value. The combined spatial-economic framework helps bridge the gap between ecosystem service research, social dimension and policy-oriented decision-making.

4.3. Contribution of CES research in southern Italy and rural regions

In Italy, many CES assessments rely on spatial models using pre-defined coefficients (Arcidiacono et al., 2016; Capriolo et al.,) or focus separately on social perceptions (Schirpke et al., 2018) and economic valuations (Bernetti et al., 2025; Fagarazzi et al., 2021; Pantaloni, 2025). This research gap is particularly evident in Basilicata. Despite its natural beauty, cultural heritage, and landscapes (Gizzi et al., 2019; Moliterni et al., 2025), few studies have assessed CES in the region. Existing research has mainly focused on specific aspects of CES. For example, Pilogallo et al. (2019) assessed geotourism potential using the InVEST tool. However, the InVEST approach relies on fixed assumptions about human responses to environmental predictors (Natural Capital Project, 2025), potentially limiting its representation of human-nature interactions.

Most Italian studies have been conducted in regions such as Tuscany (Bernetti et al., 2019; Fagarazzi et al., 2021; Paletto et al., 2023; Prete et al., 2020) and Trentino Paletto et al. (2024); Rota et al. (2025); Fagarazzi et al. (2021). Although Pantaloni (2025) highlighted the role of rural landscapes in CES provision in the Marche region, integrating assessments combining spatial and economic evaluation remain limited in Southern Italy.

By integrating these insights into regional planning, stakeholders can enhance well-being and local economic diversification, while maintaining ecological integrity. This approach supports RQ2 by demonstrating how spatial understanding of recreational demand can contribute to NBS that balance human use with conservation objectives.

The proposed framework (Fig. 5) also highlights the potential role of landscape perception integrated into CES assessments in supporting regional planning and NBS, particularly in rural contexts where CES are often underrepresented in decision-making processes. The results can support policymakers in prioritizing conservation actions, improving green infrastructure, and promoting sustainable rural development aligned with the EU Rural Vision 2040 and broader biodiversity policy objectives.

The framework can be transferred to rural regions outside Europe because it relies primarily on globally accessible environmental datasets and participatory mapping, rather than institutional recreation statistics. In many regions systematic recreation data are lacking, but digital elevation models, global population grids and open-source road networks are available. Therefore, provided that a minimum number of georeferenced recreation points can be collected through low-cost surveys or participatory GIS tools, the model's structure remains applicable. The use of open-access datasets and non-proprietary tools (QGIS.org, 2026) ensures replicability. However, recalibration of economic values is recommended to account for regional income differences and cultural preferences.

4.4. Limitations

The study relies on online survey data, which may not fully represent all recreational users. Combining online and offline questionnaires could improve representativeness. Uncertainty may also arise even from temporal discrepancies between the datasets utilized.

Additionally, this study assessed only the demand dimension of CES.

Future research should integrate supply-side accounting. This could be done, for example, by combining demand models with ecosystem condition indicators, indicator weighting (Chen and Wu, 2025), physical quality of landscapes such as green area, water ratio, naturalness (Wei et al., 2024), spatial distribution (Zhang et al., 2025), the presence of PAs (Li et al., 2025).

A limitation is that regional statistics specifically describing outdoor recreation or nature-based tourism were unavailable. Consequently, tourism categories associated with mountain and hilly environments were used as proxies for the economic part of recreational valuation. Additionally, this research applied the mean value derived from 12 value estimates, adjusted for inflation and GDP differences.

We acknowledge that model uncertainty would increase in regions where even basic geospatial datasets are unavailable or highly inaccurate. In such contexts, using coarser global datasets would reduce spatial precision and require model recalibration. Therefore, although the framework can be transferred, the accuracy of predictions depends on the quality of the available base layers.

The economic estimates presented in this study should be interpreted as order-of-magnitude approximations intended to support comparative planning rather than precise accounting figures. While regional heterogeneity in tourism demand undoubtedly exists, the spatial modeling results remain independent of the calibration factor, which affects only the scale of monetary aggregation. Future research should integrate mobile phone data, accommodation statistics at sub-regional scale, or protected area entrance records to improve calibration accuracy.

Finally, although the framework is conceptually aligned with the United Nations SEEA-EA, it does not develop formal ecosystem accounts and should therefore be interpreted as a step toward ecosystem accounting integration rather than a complete accounting implementation.

Further studies should integrate regulating ecosystem services more explicitly to capture interactions and synergies between cultural and regulating functions, particularly in protected landscapes.

5. Conclusions

Recreational CES are an important part of cultural heritage and play a significant role in how people perceive, experience, and interact with rural environments. The findings of this study, based on citizen data, a cost-effective alternative, provide valuable insights into the spatial distribution of recreational CES in rural regions. The results have relevant implications for both urban and rural planning.

The proposed framework demonstrates how citizen-generated perception data, spatial indicators, and machine learning can be combined to assess recreational CES in regions where systematic visitation surveys are limited. The methodological workflow is transferable and can be adapted to other rural contexts using locally relevant environmental, infrastructural, and perception-based datasets. Using Basilicata as a case study, we address an important gap in CES assessment in rural contexts. The integration of spatial machine learning ($R^2 = 0.76$) with economic benefit transfer (€14.64 per visit) demonstrates the methodological value of linking predicted demand with monetary estimates. Our research demonstrates that CES demand in Basilicata is strongly shaped by terrain slope, road accessibility, and presence of PAs. The framework offers a flexible tool that can support CES assessment in other rural regions with limited monitoring data.

In conclusion, by linking spatial prediction with economic valuation and situating the results within a SEEA-aligned perspective (Fig. 5), this study shows how CES assessments can directly support sustainable regional planning in rural context. Identifying where recreational demand overlaps with ecological value can help guide investments in sustainable access, conservation, and local tourism strategies that enhance both ecosystem integrity and community well-being.

CRediT authorship contribution statement

Milena V. Sokolova: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fabrizio Pedes:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. **Brian D. Fath:** Validation, Writing – review & editing. **Severino Romano:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision. **Mauro Viccaro:** Data curation, Project administration, Resources, Supervision, Visualization. **Costantino Sirca:** Investigation. **Donatella Spano:** Validation. **Mario Cozzi:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This work reflects only the authors views and opinions, neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.130405>.

Data availability

Data will be made available on request.

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