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Special Issue 2.2025

Climate crisis and spatial planning

Green infrastructure and supply of ecosystem services

The climate crisis and its impacts are affecting, with ever greater pace and intensity, urban, peri-urban, and rural contexts, thus significantly impacting the environment, local development, and quality of life. Therefore, the identification and implementation of planning actions aimed at strengthening the resilience of spatial systems and at accelerating the ecological transition are highly desirable, mainly based on the effective and sustainable use of the functions of nature and natural resources.

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The cover image: The pedestrian route of Via Chiaia in the City of Naples by TeMA Editorial Staff

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Identifying regional green infrastructure hotspots. A comparison between the Basilicata and Campania regions, Italy

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Abstract

Assessing ecosystem services (ESs), the goods and benefits provided by ecosystems and necessary to maintain human life and well-being, is important in spatial planning. Indeed, land-use changes allowed, or even driven, by spatial plans can alter ecosystem structure and functions, thereby influencing ES supply, and, ultimately, the quality of the environment and of human life. Within this framework, this study proposes a methodological approach for the identification of ES hotspots, defined as key areas that supply high levels of ESs, to support more sustainable spatial planning. The initial phase comprises a biophysical evaluation of three key regulating ESs: habitat quality, representing the capacity of ecosystems to sustain wildlife; carbon storage and sequestration, reflecting their contribution to climate regulation; and land surface temperature, serving as an indicator of local thermal mitigation offered by ecosystems. In the second phase, multiple spatial statistical methods for hotspot detection are employed in an integrated framework. Applied to Campania and Basilicata in southern Italy, the proposed approach makes it possible to compare extent and distribution of ES hotspots in the two regions. Easily transferable to other contexts where biophysical ES assessments are available, this approach provides planners with useful information to support effective planning choices.

Keywords

Carbon sequestration and storage; Habitat quality; Landsat surface temperature; Ecosystem services; Hotspot analysis

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1. Introduction

The concept of ecosystem services (ESs) refers to the set of natural functions and processes through which ecosystems generate essential benefits to human well-being (MA, 2003). These contributions may be direct, as in the case of provisioning services, or indirect, as in the case of cultural and regulating services (Balasubramanian, 2019). Regulating ESs encompass functions such as local and global climate regulation, as well as habitat provision, which serves as a prerequisite for maintaining both geological and genetic diversity. ES protection and delivery represent a central pillar of international environmental policies. Notably, one of the core objectives outlined by the Convention on Biological Diversity is to secure the conservation of at least 17% of terrestrial areas identified as critical for safeguarding biodiversity and ensuring the continued provision of essential ESs (Aichi Target 11). In practice, ecosystems generate a wide range of interrelated and mutually influencing ESs (Turkelboom et al., 2016). Decisions to prioritize the use of specific services inevitably affect the composition, magnitude, and spatial configuration of the benefits that ecosystems can deliver (Rodríguez et al., 2006). Interactions among ESs can give rise to trade-offs, whereby the enhancement of one ES results in the reduction of another, or to synergies, defined as "a situation where the use of one ES directly increases the benefits provided by another service" (Turkelboom et al., 2016, p. 2). The functional interdependencies among ESs, encompassing both synergies and trade-offs, should be systematically incorporated into ecosystem management and policy-making, as such dynamics inherently emerge during ES provision. A human tendency to maximrize a specific service may, in fact, result in the decline or deterioration of other valuable ecosystem functions and benefits (Bennett et al., 2009). In natural ecosystems, regulating services are theoretically expected to be mutually reinforcing, as they are intimately connected to the structural elements and functional dynamics of ecosystems (Burkhard et al., 2014; Hou et al., 2018). A range of empirical studies has demonstrated the presence of synergistic interactions among regulating ESs (Haase et al., 2012; Raudsepp-Hearne et al., 2010). Raudsepp-Hearne et al. (2010) developed a framework to identify recurring bundles of ESs based on spatial patterns, by analyzing 12 ESs across 137 municipalities in Québec, Canada.

Identifying and characterizing areas that harbor high levels of biological diversity and support critical ecological functions constitutes a fundamental step toward the effective implementation of international environmental sustainability directives (Naidoo et al., 2008). From the perspective of environmental governance and decision-making support, adopting an integrated approach that accounts for the full spectrum of relevant ESs, as well as the potential synergies and trade-offs among them (Kandziora et al., 2013), is therefore essential.

Building upon these conceptual foundations, a growing corpus of scholarly research has concentrated on the spatial delineation of ES hotspots, generally characterized as zones exhibiting elevated levels of service heterogeneity, and a strong inherent capacity to generate ecosystem benefits; conversely, areas with minimal values along these dimensions are classified as coldspots (Schröter & Remme, 2016). The rising academic interest in ES hotspots can be attributed to the fact that hotspot mapping and evaluation can support the geographic targeting of high-priority zones for conservation strategies (Blumstein & Thompson, 2015), assist in assessing the performance and outcomes of biodiversity protection measures (Spanò et al., 2017), and inform decision-making regarding the spatial coordination of ES trade-offs and co-benefits (Bagstad et al., 2017). Indeed, mapping hotspots provides a valuable basis for formulating evidence-based conservation boundaries and for establishing spatial priorities in biodiversity protection, particularly under constraints of limited financial or managerial resources during ecosystem planning and governance (Reyers et al., 2009).

Although numerous efforts have been made to spatially represent hotspots, decision-makers still exhibit limited awareness of the potential of spatial planning as a tool for guiding the distribution and sustainable use of these services (Schröter et al., 2017).

Building on this conceptual framework, this study proposes a two-stage methodological approach for the spatial identification of ES hotspots, defined as areas capable of providing high levels of ESs. This approach was applied to two case studies, i.e., the Basilicata and Campania regions, in Italy. The first stage involves the spatial assessment of three regulating ESs: i., local temperature regulation, using land surface temperature (LST) as a proxy; ii., lifecycle maintenance, habitat and gene pool protection, evaluated through habitat quality (HQ), under the assumption that higher habitat quality corresponds to greater support for lifecycle functions and biodiversity conservation; and iii., global climate regulation, assessed through carbon storage and sequestration (CSS). These three ESs were mapped for both case studies using three distinct methodologies. The mapping of LST was conducted using satellite data. The mapping of HQ and CSS was conducted using two models from the InVEST suite (Integrated Valuation of Ecosystem Services), a free, open-source spatial modelling platform developed by the Natural Capital Project[1]. This versatile modelling framework supports the evaluation and cartographic representation of ESs, facilitating the comparison of alternative land-use scenarios and estimating their respective environmental consequences (Jiang et al., 2017). The second phase of the methodology focuses on the evaluation and mapping of ES hotspots, employing multiple spatial statistical techniques. These include the Local Indicator of Spatial Autocorrelation (LISA), its median variant, the Getis-Ord G* statistic, and a quantile-based approach. This phase is implemented through a structured four-step procedure.

The paper is organized into five sections. The second section describes the study areas, and the methodologies used to map the three regulating ESs and identify hotspots. The third section presents the results: the spatial distribution of the services and their hotspots in Basilicata and Campania. The fourth section discusses the findings, while the fifth section offers concluding remarks, highlights the strengths and limitations of the applied methodologies, and outlines directions for future research.

2. Materials and methods

2.1 Study areas: the regional contexts of Basilicata and Campania

Located in the southern part of Italy, the Basilicata region covers nearly 10,000 square kilometers and it is bordered by Campania, Apulia, Calabria, and the Ionian coastline (Fig.1). The territory is predominantly composed of mountainous and hilly areas, with only around 10% consisting of flatlands, mostly concentrated on the Metapontino coastal plain. The western portion includes the Lucanian Apennine, with notable mountain groups such as Pollino, Volturino, and Sirino. By contrast, the eastern hills slope down towards the Ionian shoreline. Basilicata's fluvial network primarily channels water into the Ionian Sea through rivers like Bradano, Basento, Cavone, Agri, and Sinni. Other watercourses, such as Ofanto, Platano, Melandro, and Noce, flow into either the Adriatic or the Tyrrhenian Sea. The region's hydrological framework, segmented into eight drainage basins, exhibits a typical torrential flow regime, marked by considerable seasonal variability and a tendency for flooding in the lower courses. The main settlements are Potenza, situated in the northwest, and Matera, located toward the eastern edge. About one-fifth of the regional territory benefits from environmental protection under National Law no. 1991/394, involving two national parks, three regional parks, eight state-level nature reserves, and seven regional reserves. Furthermore, Basilicata hosts 82 designated Natura 2000 sites. As of 2024, the regional population stands at 533,636 inhabitants, distributed across 131 municipalities, the latter organized into two provinces. The main settlements are Potenza and Matera, respectively home to around 67,300 and around 60,400 residents.

Campania extends over an area of about 13,700 square kilometers, bounded by Lazio, Molise, Apulia, Basilicata, and the Tyrrhenian Sea (Fig.1). The topography is predominantly made up of hills and mountains, with flatlands, mostly alluvial in origin, accounting for 14% of its surface. This geographic diversity includes the Campanian Plain and the Sele estuary, inside alluvial basins, and prominent limestone massifs rising over 2,000 meters, such as the Matese, Sannio, Irpinia, and Cilento ranges. The coastal landscape is further shaped

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[1] https://naturalcapitalproject.stanford.edu/software/invest (last accessed 2025/06/25)

by volcanic features, notably the extinct Roccamonfina volcano and active volcanic systems including the Somma-Vesuvius complex and the Phlegraean Fields–Ischia area. The hydrological system is characterized by perennial rivers in the mountainous zones, episodic torrents in the uplands, and artificial or moraine channels along the coastline. Key water streams include the Volturno and Sele rivers.

As of 2024, Campania includes two national parks, four marine protected areas, nine regional parks, five state-managed nature reserves, and four regional nature reserves. The region also hosts 137 Natura 2000 sites. With a population of 5,590,076 inhabitants distributed across 553 municipalities, Campania is organized into five provinces. Major metropolitan areas include Naples, which contains 2,967,736 residents, followed by Salerno (1,057,819) and Caserta (906,080).

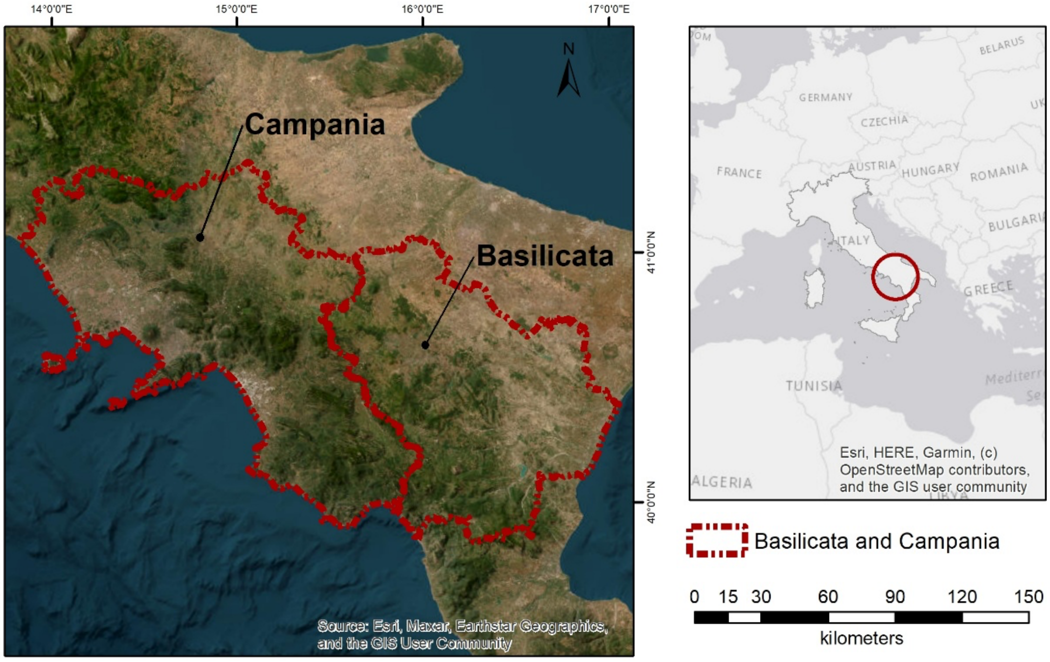

Fig.1 Study areas: Campania and Basilicata, and their location in Italy

2.2 Ecosystem service mapping

This section briefly outlines the approaches employed to assess and map the three regulating ESs, local temperature mitigation through the evaluation of LST, lifecycle maintenance, habitat, and gene pool protection where HQ is a proxy, and CSS.

LST is widely recognized as a fundamental geophysical variable for quantifying surface-atmosphere energy fluxes and assessing thermodynamic behavior at the land interface (Olivera-Guerra et al., 2025). It constitutes a key element in the investigation of climate-sensitive processes, including the characterization of urban thermal anomalies, quantification of evapo-transpirative fluxes, and analysis of surface energy balance across heterogeneous land cover types. Moreover, LST modulates near-surface air temperatures and contributes to multiscale climatic feedback operating at both local and global levels (Guillevic et al., 2018). The advent of high-resolution thermal remote sensing technologies, particularly through satellite platforms like Landsat 8–9 equipped with Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), has significantly enhanced the ability to monitor these processes across vast regions (Zhang et al., 2006; Sánchez-Aparicio, 2020).

Following the method developed by Lai et al. (2020), this study focuses on the spatial distribution of LST in Campania and Basilicata. Satellite data were retrieved from the Landsat Collection 2 Level-2 (OLI/TIRS) via the USGS Earth Explorer platform[2]. The thermal band B10, with a spatial resolution of 30 meters, was employed for extracting LST values. Data collection was limited to the summer 2023 period, from June 25 to

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[2] https://earthexplorer.usgs.gov/ (last accessed 2025/06/25)

September 2, with a strict cloud cover threshold of 6%. Due to the spatial limitations of individual satellite scenes, in Campania multiple images were required to achieve full regional territory coverage.

For Basilicata, a set of images was retrieved, each covering the entire region; a total of five satellite images were available for this time period. For Campania, 21 satellite images were retrieved; these were grouped into sets of three to four images, based on scene and acquisition date, to fully cover the regional area.

Each set was mosaicked and evaluated, with those showing the highest thermal means retained for the final LST composite map. The process of selecting and analyzing the raster images entailed multiple steps. After merging image sets corresponding to the same acquisition date and scene, statistical verification of minimum and maximum values was conducted. In Campania, partial overlaps between the northwestern and northeastern image subsets were addressed through the calculation of mean LST differences within the overlapping areas. Subsequently, a clipping procedure was applied to produce the final unified LST map.

HQ was determined by employing the InVEST habitat quality model (Sharp et al., 2018), widely used because of its rapid data availability, powerful analytical capabilities, intuitive functionality, effective data processing, accurate outputs, clear result visualization, low implementation costs, and ease of adaptability to diverse contexts (Gao et al., 2017; Li et al., 2021; Yang, 2021). The model combines information on habitat suitability and threats to biodiversity to assess the overall habitat quality (Wu et al., 2021). It works on the assumption that habitat degradation intensifies depending on the sensitivity of the habitat to a set of threats (Aneseyee et al., 2020). Typically, the effect of a threat on a habitat decreases proportionally to the growing distance from the degradation source (Ibid.).

The assessment attributes numerical scores ranging from 0 to 1; rather than representing an absolute evaluation, they allow for comparison between various parts of the territory (Natural Capital Project, n.d.). The values of this relative index are finally depicted on a gradient map (Chiang et al., 2014). Required data for the model encompass a Land Use Land Cover (LULC) map, threat raster maps, a threat table, a sensitivity table, and the half-saturation constant (Natural Capital Project, n.d.). The LULC map constitutes the basis for defining the habitats; the threat raster maps provide the spatial features of the threats; the threat table specifies the characteristics of the threats, such as the impact weight, the maximum distance within which they influence a habitat, and the decay function; the sensitivity table illustrates the potential for each LULC to be a habitat and its vulnerability to the analyzed threats; and the half-saturation constant represents the point at which habitat quality is halved, meaning the habitat's ability to support biodiversity is reduced by 50% (Ibid.).

For this study, the LULC map is extracted from the CORINE Land Cover database. Following Sallustio et al. (2017), the analyzed habitats are as follows: beaches, dunes and sand; water bodies; wetlands; grasslands; shrublands; broadleaved forests; conifer forests; mixed forests; inland unvegetated or sparsely vegetated areas; intensive agriculture; extensive agriculture; buildings and other artificial areas or impervious soils; and open urban areas. The list of threats considered in this analysis includes primary, secondary, tertiary, residential, and service roads; railways; intensive and extensive agricultural areas; and buildings, other artificial surfaces, or impervious soils. The mapping of the threats relies on open-source data obtained from OpenStreetMap (OSM), while the threat and sensitivity tables are drawn from Sallustio et al. (2017). The half-saturation constant is initially set to the default value of 0.5 and subsequently to half of the maximum habitat degradation value determined by the model in the first run.

In relation to CSS, the assessment and spatial quantification is carried out using the "Carbon Storage and Sequestration" model, part of the InVEST toolkit (Natural Capital Project, n.d.). The CSS model estimates total carbon stock in relation to four carbon pools: aboveground biomass (AB), belowground biomass (BB), dead organic matter (DM), and soil organic matter (SM). AB encompasses all living plant material located above the soil surface, whereas BB refers to the root biomass associated with the AB. DM comprises decomposing vegetative material such as leaf litter and dead wood. SM, typically the largest carbon reservoir, consists of the organic fraction embedded in the soil.

This model has been employed across a wide range of geographical contexts and disciplines. For instance, García-Ontiyuelo et al. (2024) applied it to estimate carbon sequestration in coastal forest ecosystems in southern Galicia, thereby informing strategies for sustainable forest management. Similarly, Rachid et al. (2024) used the model to assess the climate regulation potential of urban green spaces in the City of Nador, aligning the findings with local climate policy objectives.

The implementation of the CSS model necessitates two primary input datasets: i., a table in .csv format that contains carbon density values (expressed in megagrams per hectare) associated with each land cover class for one or more carbon pools; ii., a land cover map.

In the present analysis, three carbon pools (AB, DM, SM) were modelled using the InVEST model. BB values were subsequently integrated by superimposing the model outputs with the global carbon dataset developed by NASA's Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC), allowing for the aggregation of carbon values.

The carbon density figures used in the .csv file were derived from a range of validated sources. For AB and BB, data were obtained from the global carbon maps provided by NASA's ORNL DAAC. The National Inventory of Forests and Carbon Sinks (2015 edition) was referenced for AB and DM, and the 2005 edition for SM. Additional SM-related data were sourced from the Italian Institute for Environmental Protection and Research (ISPRA) and the Regional Agricultural Research Agency of Sardinia (Agenzia Regionale per la Ricerca in Agricoltura della Sardegna). Land cover classification was based on the 2018 Corine Land Cover (CLC) dataset, made available through the Copernicus Program.

2.3 Hotspot delineation

Following Bagstad et al. (2017), the numerous methods for detecting hotspots can be categorized into three types: approaches based on i., indices of spatial autocorrelation; ii., quantile rankings, or, iii., area. Additionally, various strategies have been proposed for delineating multi-service hotspots (Schröter & Remme, 2016). The identification of hotspots is method-dependent, with differing techniques often producing divergent results (Schröter & Remme, 2016; Bagstad et al., 2017), and "interesting locations" are those that consistently emerge as clusters regardless of the chosen approach (Anselin, 2024). Consequently, four distinct methods are here applied to delineate hotspots for individual ESs: LISA, its median variant, the Getis-Ord G* statistic, and a quantile-based approach.

LISA encompasses a class of statistical measures that assess the degree of significant spatial clustering of similar attribute values surrounding each observation (Anselin, 1995). In GeoDa (Anselin, 2024), LISA is operationalized through a localized version of Moran's I, with a moving window centered on each spatial unit; the window's dimension and shape is determined by the selected contiguity criterion. The outcome is a cluster map that classifies spatial units, at specified levels of statistical significance, into three categories: hotspots, coldspots, and spatial outliers, depending on whether the values within a given spatial unit and its neighboring units are above or below the mean value. A variant of this approach is the median LISA statistic, which substitutes the mean with the median value to mitigate the influence of outliers.

The third spatial statistic here employed is the local G* index, defined as the ratio between the sum of values within this window and the total sum of values across the entire dataset (Getis & Ord, 1992; Ord & Getis, 1995). Like LISA, the G* statistic operates through a moving window centered on the focal spatial unit; unlike LISA, the G* statistic exclusively identifies hotspots and coldspots, omitting spatial outliers (Anselin, 2024).

The fourth approach utilized is a quantile-based one, with a threshold set at the 90th percentile, thus designating as hotspots the top-richest cells.

A four-step procedure was implemented. Fists, a vector-based grid comprising 200*200-meter square cells, encompassing the two designated study areas, was developed and the average values of the three selected ESs were calculated for each cell and assigned as attributes using zonal statistics. The cell size was empirically chosen to optimize resolution and processing efficiency. Next, the four hotspot detection techniques were independently applied to each ES for both study areas, resulting in four distinct hotspot maps for each ES. The third step entailed intersecting the four hotspot maps corresponding to each ES. Finally, a further intersection was conducted to identify multi-service hotspot cores.

3. Results

3.1 The spatial distribution of ecosystem services

This section examines the spatial patterns of the three selected ESs across the Campania and Basilicata regions.

The spatial distribution of LST varies across the two regions.

In Basilicata, only one image (Landsat scene 188, row 32) suffices to cover the regional territory. Among the analyzed images, the one having the highest mean value, dating July 18, 2023, was chosen; on that day, LST values ranged from 24.42 °C to 62.54 °C, and their spatial layout is provided in Fig.2. Higher temperatures are concentrated in industrial, commercial, and agricultural zones in the northeast, notably the Bradano River basin (Alto Bradano, Venosa, Vulture Hills), and the urban area of Matera. High LST values are also found on the Metapontino Plain and Ionian coast. Cooler values are recorded along the Lucanian Apennines, particularly near Mount Vulture, Mount Volturino, and the Pollino National Park. Once the 2018 CLC map is overlaid, the highest mean LSTs (48.04–49.10 °C) occur in irrigated cropland (CLC 212), heterogeneous agriculture (CLC 241), and artificial surfaces (CLC 111, 121). The lowest (32.61–37.59 °C) are found in water bodies (CLC 512), forests (CLC 311, 313), and rocky areas (CLC 332).

Campania's LST map was generated by merging Landsat scenes 189 (west), rows 31-32, dating July 17, 2023, and 190 (east), rows 31-32, dating August 25, 2023. Regional LSTs range from 27.5 to 64.5 °C, and their spatial layout is provided in Fig. 2. Values peak in urbanized zones of the northwest, including Naples' coastal hills, the Campanian and Phlegraean plains, and around the Vesuvius crown. High temperatures also occur in agricultural zones of Avellino and Benevento (Alto Tammaro and Alto Fortore) and Salerno's Sele Plain. Cooler LSTs are observed in the mountainous Apennine belt; the highest mean LSTs (47.6–53.3 °C) occur in artificial areas (CLC 111, 112), while lower values (34.3–39.4 °C) are typical of water bodies, forests (CLC 311-313), and herbaceous vegetation (CLC 323-324).

As for HQ, the habitat quality level varies across the two regions (Fig.3). The average value for Basilicata is 0.51, while for Campania it is 0.49. Low levels characterize 44.45% of Basilicata and 40.61% of Campania, while medium values are found in 19.50% of Basilicata's territory and 27.96% of Campania's. In contrast, superior levels are found in 36.05% of Basilicata and 31.43% of Campania. The highest levels are observed in natural environments, which frequently overlap with designated protected areas. Noteworthy examples are the National Parks of Pollino and Appennino Lucano Val d'Agri Lagonegrese; the Regional Park of Gallipoli Cognato and the Piccole Dolomiti Lucane; the Vulture Regional Natural Park; and the Matera Rupestrian Churches Archaeological, Historical, and Natural Regional Park in Basilicata. Vallo di Diano e Alburni National Park, Vesuvius National Park, Valle delle Ferriere State Reserve, Picentini Mountains Regional Park, Partenio Regional Park, Taburno Camposauro Regional Park, Roccamonfina-Foce Garigliano Regional Park, and Matese Regional Park are also remarkable instances in Campania. Conversely, the lowest levels mostly concern anthropized areas including both urban zones and agricultural lands. In Basilicata, low values are identified within the urban areas of Potenza and Matera, as well as in the agricultural lands of the Metapontino, Agri, Vulture Melfese, Alto Bradano, Sauro, and Ofanto Valley regions.

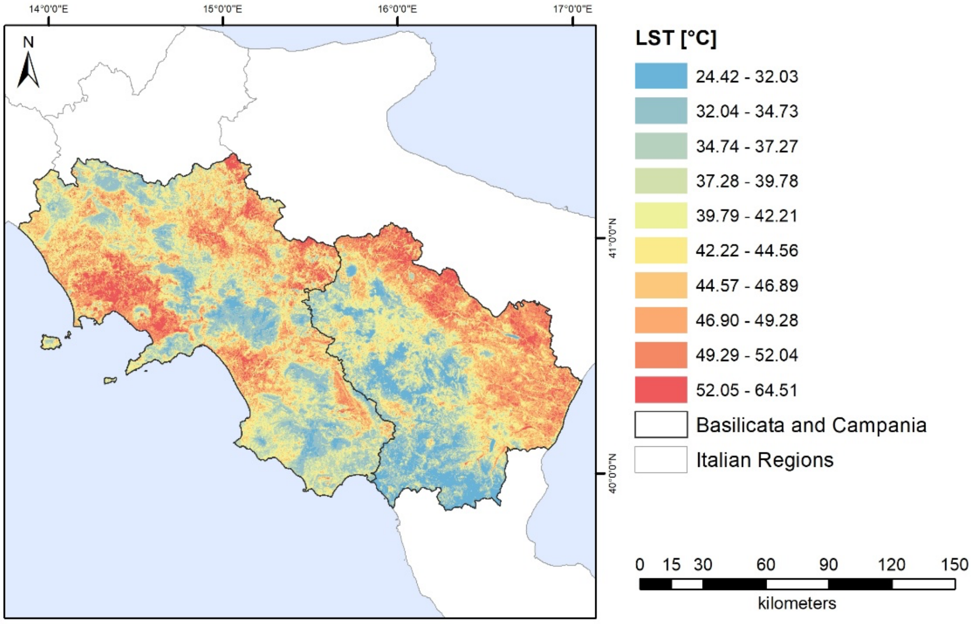

Fig.2 Spatial pattern of LST on the hottest day of Summer 2023 in Campania and Basilicata (dates vary by region)

Similarly, in Campania, poor habitats characterize the urban areas of Naples, Salerno, Caserta, Benevento, and Avellino, as well as the agricultural areas of the Sele Plain, the Acerrano-Nolano Agro, the Nocerino-Sarnese Agro, the Ufita Valley, the Coastal Cilento Hills, and the Taburno Mountain-Telesina Valley. With reference to habitat types, broadleaved forests, grasslands, and wetlands exhibit the highest levels of habitat quality, while buildings and other artificial areas or impervious soils, open urban areas, and intensive agricultural lands show the lowest levels. Meanwhile, conifer forests, water bodies, beaches, dunes, and sands, extensive agricultural land, and inland unvegetated or sparsely vegetated areas present intermediate levels of progressively lower habitat quality.

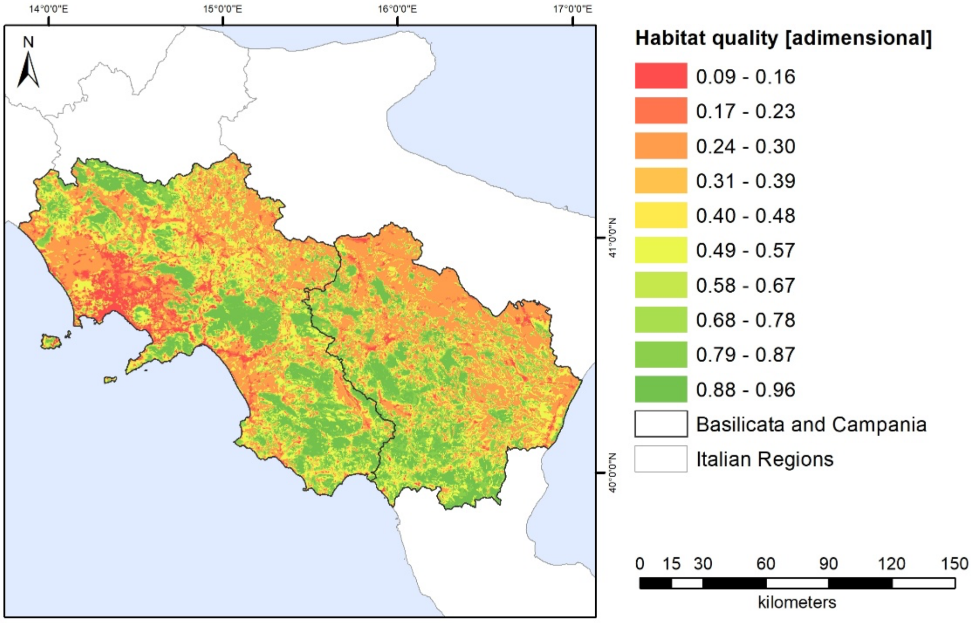

Fig.3 Spatial distribution of Habitat quality (HQ) in Campania and Basilicata

Fig.4 presents carbon storage values, expressed in megagrams per 900 square meters (Mg/900 m^2), across the Basilicata and Campania regions. In relation to Basilicata, CSS values range from 0 to 19.11 Mg/900 m^2. Three high-density clusters are located in the northeast, near Mount Santa Croce, Bosco Grande, and the protected areas of Monticchio Lake and Grotticelle. Two smaller clusters appear in central Basilicata, in proximity to the Pollino and Appennino Lucano National Parks and the Regional Parks of Gallipoli Cognato and the Lucanian Dolomites. The southwest shows moderately high values without distinct clustering, while the eastern sector displays the lowest values, especially near urban and aquatic zones. The highest average values correspond to forest classes (CLC 311, 312, 313), ranging from 13.3 to 11.6 Mg/900 m^2. Intermediate values (7.9–7 Mg/900 m^2) are linked to salt marshes, salines, shrubs, sparsely vegetated areas, and pastures. Agricultural lands exhibit lower values (6.8–3.4 Mg/900 m^2), while artificial areas and water bodies show the lowest carbon storage levels. In relation to Campania, carbon storage values range from 0 to 21.54 Mg/900 m^2. Two major clusters are observed in the southern and central zones, with smaller ones in the north. High carbon densities are concentrated in protected areas, including the Roccamonfina-Garigliano, Matese, Taburno-Camposauro, Trebulani Mountains, and Partenio Regional Parks in the northwest; Vesuvius National Park, Tirone Alto Vesuvius Reserve, and the Lattari, Picentini, and Eremita-Marzano Mountain parks in the center; and the Cilento and Vallo di Diano National Park in the south. The highest average values are recorded in broad-leaved, coniferous, and mixed forests (CLC 311, 312, 313), ranging from 15.82 to 13.7 Mg/900 m^2. Moderately high values (9.46–7.5 Mg/900 m^2) are associated with sparsely vegetated areas, burnt zones, natural grasslands, sclerophyllous vegetation, transitional woodland-shrub, pastures, and marshes. Artificial surfaces and water bodies exhibit the lowest values, typically below 1 Mg/900 m^2.

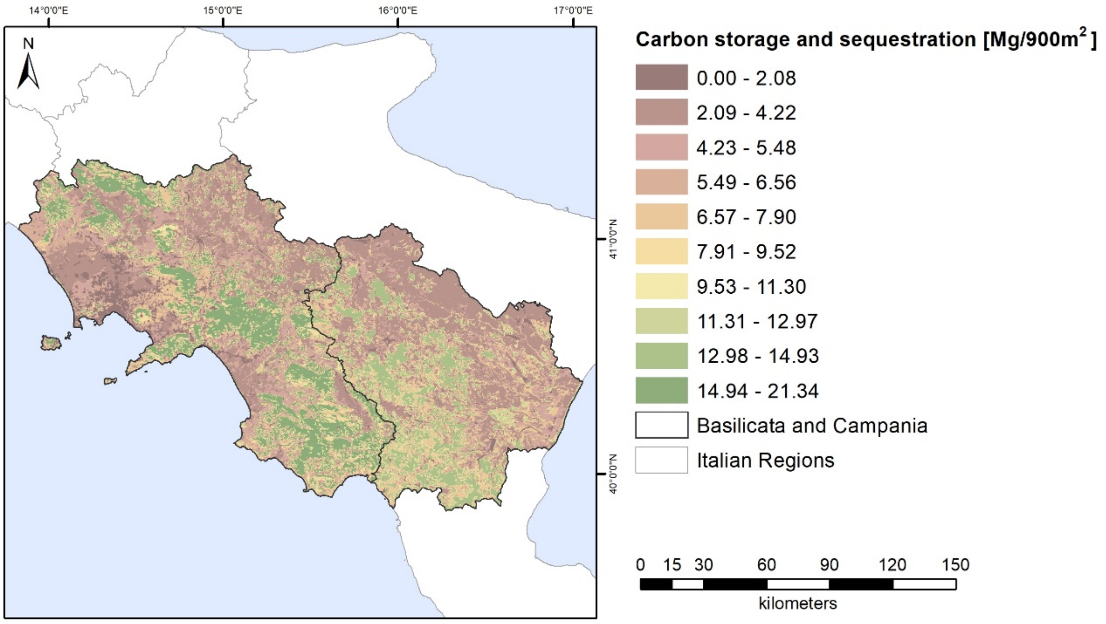

Fig.4 Spatial layout of Carbon storage and sequestration (CSS) in Campania and Basilicata

3.2 Ecosystem service hotspots

Fig.5 presents the results of the hotspot analysis, illustrating the spatial distribution of individual ESs hotspots (panels A-C) and multi-service hotspots (panel D), that is, areas simultaneously identified as hotspots for all three ESs discussed in Sections 2.2 and 3.1. In Campania, approximately 9.8% of grid cells were classified as hotspots for the three regulating ESs when considered individually. In Basilicata, 9.7% of cells were hotspots for CSS and HQ, increasing to 9.9% for local temperature mitigation. In contrast, multi-service hotspots accounted for only 4.058% in Basilicata and 4.686% in Campania.

Fig. 6 provides a more detailed view of ES hotspot interactions. Panel A distinguishes between single- and multi-service hotspots, specifying which ESs each cell supports as a hotspot core, whereas panel B offers a synthetic index, expressing the number of ESs for which each cell functions as a hotspot core. Quantitative information on categories shown in Fig.6 is provided in Tab.1.

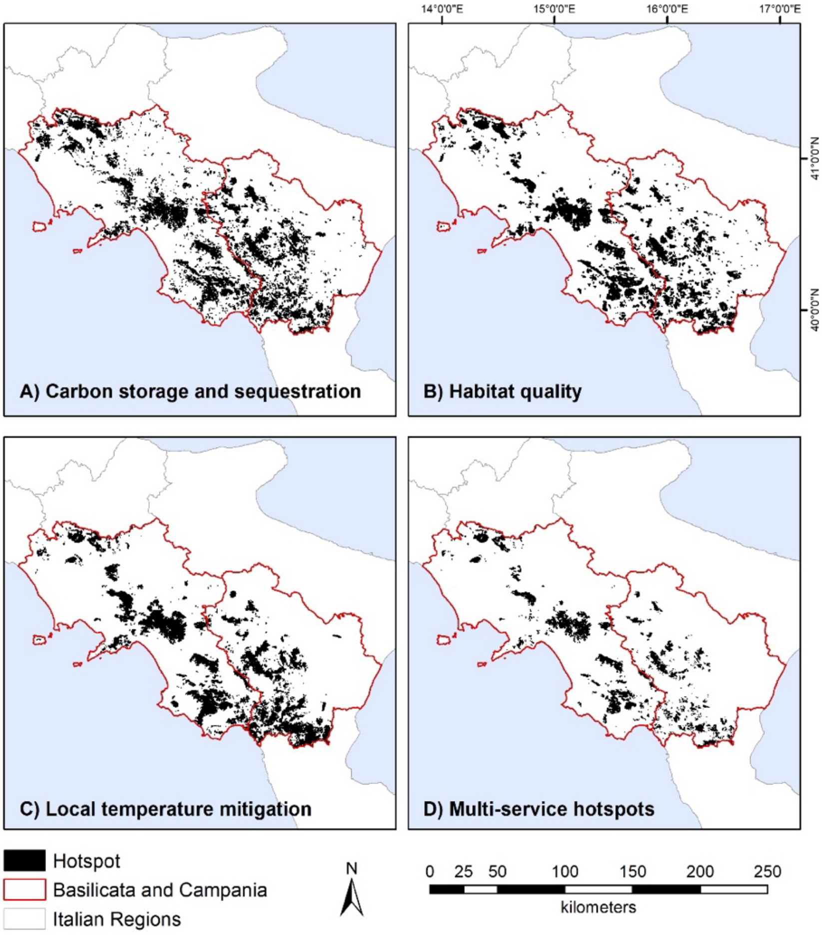

Fig.5 Spatial distribution of individual hotspots (panels A, B, and C) and of hotspot cores for the three ESs (panel D)

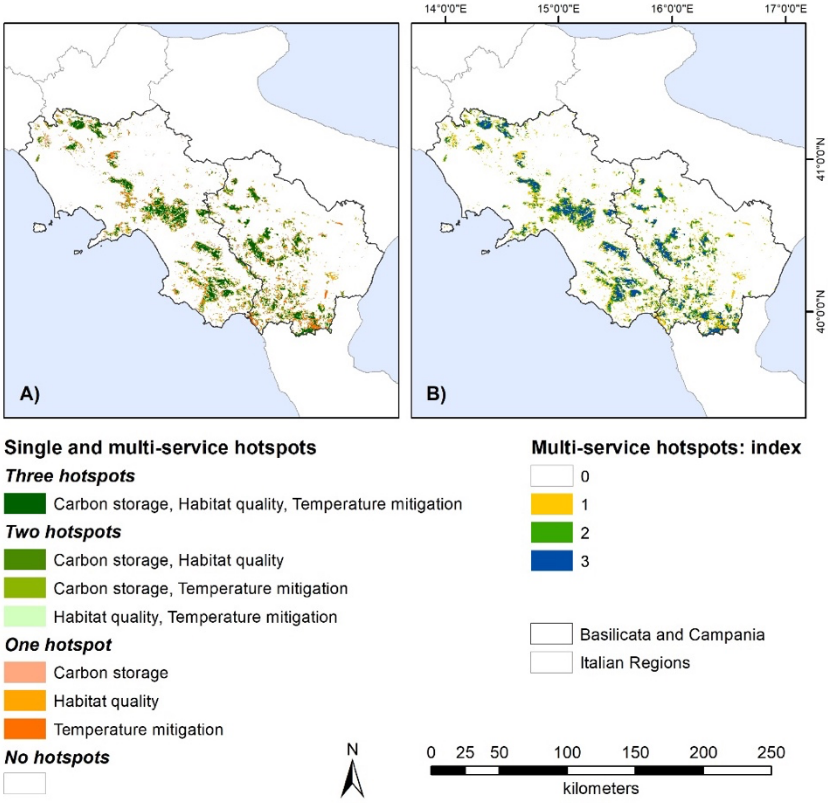

Fig.6 Single and multi-service hotspots (panel A) and a synthetic index of multi-service hotspots (panel B)

Index	Combination of ESs for which a cell performs as hotspot core	Basilicata (% of cells)	Campania (% of cells)
3	Carbon storage & Habitat quality & Local temperature mitigation	4.058 %	4.686 %
2	Carbon storage & Habitat quality	2.353 %	1.912 %
	Carbon storage & Local temperature mitigation	1.326 %	1.179 %
	Habitat quality & Local temperature mitigation	1.371 %	1.670 %
1	Carbon storage only	1.997 %	2.094 %
	Habitat quality only	2.001 %	1.689 %
	Local temperature mitigation only	3.238 %	2.451 %
0	*No significant hotspots*	83.655 %	84.318 %

Tab.1 Multi-service hotspot index and relevance of each multi-service combination in Basilicata and Campania

4. Discussion

The identification and spatial characterization of ES hotspots have become increasingly common in recent literature, as they provide a spatially explicit foundation for prioritizing conservation, land-use planning, and ecosystem-based management. This study, which reveals a relatively low co-occurrence of regulating ESs in multi-service hotspots in Campania and Basilicata (around 4–5% of the landscape), aligns with a growing body of research suggesting that multifunctionality is relatively rare in many socio-ecological systems (e.g., Fratini, 2023).

A comparable result was found by Qiu & Turner (2013), who analyzed ES bundles in the Yahara Watershed, in the US, and found limited spatial overlap of regulating services, with synergistic effects highlighted for carbon storage, regulation of water quality and of soil erosion. Similarly, Ran et al. (2020) identified trade-offs and synergies across three regulating ESs in southwestern China and observed negligible percentages of multifunctional landscapes, providing all of the three selected ESs. Studies that report higher degrees of spatial congruence among regulating ESs are often situated in ecosystems with extensive natural or semi-natural land cover. For instance, the study by Felipe-Lucia et al. (2018) found that regulating ESs frequently co-occur in forests, suggesting that ecosystem integrity plays a crucial role in enabling ES synergies.

The moderate congruence unveiled in this study is therefore consistent with previous global research. Moreover, Mediterranean landscapes, such as Basilicata's and Campania's ones, are often fragmented (Zullo et al., 2015), characterized by mosaics of forest, shrubland, farmland, and urban settlements, each contributing differently to individual ESs, which might explain the relatively low proportion of multi-service hotspots landscape as a reflection of the trade-offs between human land use and ecosystem functionality (DeFries et al., 2004), a phenomenon well documented in the European context. One factor that might be contributing to the moderate convergence across ESs in Basilicata and Campania is their sensitivity to underlying physical characteristics, as the two regions are heterogeneous in terms of topography, climate, soil characteristics, and land covers: as Crouzat et al. (2015) show, landscape heterogeneity can promote ecosystem multifunctionality at the regional scale, but such services often occur in separate patches due to specialization in land use and management. This could explain why, in the two analyzed regions, single service hotspots are distributed across the landscape, but the level of hotspot overlaps remains moderate.

A second factor to be considered is land management. In Campania, extensive urbanization and industrial agriculture have led to land-use specialization in large parts of the region, resulting in spatial concentration of regulating ESs in areas that are marginal for agriculture. Moreover, in Basilicata a strong difference between the eastern and western parts is highlighted: lower population density and prevalence of extensive pastoralism and traditional agricultural practices to the west have possibly contributed to preserving some degree of multifunctionality, leading to the western hotspot clusters. These patterns align with findings from a study by Foley et al. (2005), who observed that intensively managed landscapes tend to sacrifice regulating ESs in favor of provisioning ones.

The results of this study provide relevant implications for spatial planning and policy: since only a very small percentage of the landscape functions as multi-service hotspots, both land protection and ecosystem enhancement strategies need to be considered, depending on whether the area to be planned or managed performs as a single or multi-service hotspot, or is not identified as a hotspot at all.

From a conservation planning perspective, multi-service hotspots represent high-value targets due to their concentrated ecological benefits: to put it with Raudsepp-Hearne et al. (2010), areas that provide multiple regulating ESs are more resilient. As a result, they can provide larger long-terms returns for conservation investment (Kovacs et al., 2013) and could be therefore prioritized for public land purchasing, or for strict conservation as natural protected areas, or for protection in landscape plans (Cialdea, 2021) pursuant to the European Landscape Convention[3].

The large proportion of cells classified as non-hotspots in both Basilicata and Campania suggests a vast potential for ES enhancement through targeted interventions. Spatial planners could use hotspot maps such as the ones here produced to guide green infrastructure (GI) identification in local and regional plans, with single or multi-service hotspots serving as nodes of the GI, hence as priority zones to be connected through appropriate ecological networks. To this end, peri-urban zones or degraded rural landscapes not identified as ES hotspots could be managed to improve their ES supply by increasing tree cover, or by enhancing green connectivity through treed roads, hedgerows, or vegetative riverbanks and buffers. At the municipal scale, hotspot delineation could be integrated into local development plans to guide the siting of public green spaces, for instance to maximize the potential uptake of ESs by bridging areas rich in ES supply with demanding areas, i.e., residential zones, or within sectoral plans, as in the case of the urban greenery plan of the municipality of Trento (Comune di Trento, 2024, pp.75-80), a pioneering example of hotspot mapping integration in spatial planning. This is consistent with Lovell & Johnston (2009), who advocate for multifunctional landscapes that integrate ESs into spatial design, rather than confining them within designated conservation zones. Moreover, the findings could inform strategic environmental assessments (SEA) and environmental impact assessments (EIA) by providing a spatial baseline of ES provision: in this context, proposed development or infrastructure projects could be evaluated in relation to their interference with ES hotspot maps, thereby facilitating the integration of ecological costs into planning decisions.

5. Conclusions

This study combines established biophysical modelling with a comprehensive suite of spatial statistical techniques to define a two-phase methodological framework for the identification of regulating ES hotspots, which are areas of high ecological value due to their simultaneous provision of elevated levels of ESs. In the first phase, three key regulating ESs, CCS, HQ, and LST, are assessed using satellite data and InVEST models. In the second phase, individual and multi-service hotspots are identified through a four-step integration of four statistical methods, i.e., LISA, median LISA, the local G*, and the quantile-based segmentation. The application of the methodology to Basilicata and Campania provides important insights.

The results reveal that single-service hotspots are widely distributed across the landscape; however, the spatial overlap among them remains moderate, confined to roughly 4–5% of each region. This limited overlap is likely due to landscape fragmentation and land-use practices that foster specialization, ultimately generating trade-offs between human land use and ecosystem functionality, and causing the spatial separation of individual ESs. Since this study captures a single point in time, future research could assess how the distribution and size of hotspots change over time, ideally complemented by a longitudinal analysis of the driving factors, such as urbanization and shifts in both intensive and extensive agricultural practices. This latter aspect is particularly

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[3] https://rm.coe.int/16807b6bc7 (last accessed 2025/06/25)

significant, from a policy perspective, for marginal rural areas and mountain villages affected by depopulation and farmland abandonment.

The approach here proposed offers a valuable evidence-based tool for spatial planning and decision-making. Indeed, the identification of ES hotspots allows for both the definition of conservation efforts to preserve their ecological functions, and the development of policies aimed at enhancing their functionality and increasing the services they provide. Conservation efforts should prioritize landscapes delivering multiple ESs, whereas non-hotspot zones represent strategic opportunities for ecosystem enhancement. In order to balance conservation and sustainable land use, ESs should also be incorporated into spatial plans, SEA, and EIA. As shown in Section 3, several regulating ES hotspot cores are already located within established natural protected areas, such as national and regional parks. Future research could therefore examine whether, and to what extent, the existing planning tools for these protected areas take ESs and GI into account. Analyzing the relevant planning provisions related to hotspot areas would also be valuable, as it could offer insights into their potential future evolution.

More in-depth research is required to better understand the specific drivers and spatial factors contributing to the observed low spatial overlap of regulating ESs, thus enabling more targeted and effective planning interventions. Furthermore, future research might include additional regulating ESs, as well as provisioning and cultural ESs to offer a comprehensive understanding of ES interactions.

The demonstrated applicability of the methodology across two Italian regions highlights its adaptability to other contexts where similar input datasets are available. Applying it to different contexts and integrating it with socio-economic data would further increase its role in promoting climate neutrality and adaptation to climate change while fostering development and well-being.

Authors’ contributions

F.I., S.L., F.Leccis and F.Leone collaboratively designed this study. Individual contributions are as follows: F.I. wrote Section 2.1; S.L. wrote Sections 2.3, 3.2, and 4; F.Leccis wrote Section 5: F.Leone wrote Section 1. F.I., F.Leccis and F.Leone jointly wrote Sections 2.2 and 3.1.

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Image sources

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